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As a result of my oral presentation on 30 June 2026 the Planning Inspectorate requested that I submit a selection of research papers upon which I have relied when compiling the high level summary that I delivered verbally and submitted in written form.
The clinical studies and various analyses relate to the known health impacts that the proposed Lime Down Solar would have on the current and future families living in the many North Wiltshire villages affected by Lime Down Solar over the next 60 years.

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Nature and Health

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Keywords

greenspace, green space, green infrastructure, landscape, parks, urban forests, community gardens

Abstract

Urbanization, resource exploitation, and lifestyle changes have diminished possibilities for human contact with nature in many societies. Concern about the loss has helped motivate research on the health benefits of contact with nature. Reviewing that research here, we focus on nature as represented by aspects of the physical environment relevant to planning, design, and policy measures that serve broad segments of urbanized societies. We discuss difficulties in defining "nature" and reasons for the current expansion of the research field, and we assess available reviews. We then consider research on pathways between nature and health involving air quality, physical activity, social cohesion, and stress reduction. Finally, we discuss methodological issues and priorities for future research. The extant research does describe an array of benefits of contact with nature, and evidence regarding some benefits is strong; however, some findings indicate caution is needed in applying beliefs about those benefits, and substantial gaps in knowledge remain.

Erratum

INTRODUCTION

The public health field views the natural environment with ambivalence. Infectious agents, extreme weather, and geological events regularly sicken, injure, and kill people, often en masse. Yet, people cannot remain healthy without clean air, clean water, food, and other resources provided as "ecosystem services." Enormous amounts of research inform these contrasting perspectives, describing how the natural environment harms humans, how health depends on the natural environment, and how human impacts on the natural environment rebound on health.

A theme that has become increasingly distinct over recent years concerns the natural environment, or "nature," perceived, valued, and engaged with as such, particularly in urbanized societies. This research focuses primarily on benefits of contact with nature. Key segments of this literature are young, but central ideas, such as the link between vegetation and air quality, have ancient provenance in the public health field (82). Interventions prompted by those ideas, such as urban parks, have long remained in place, presumably because the public has enjoyed them and believed in their salutary value. The recent research tests such beliefs, and it encourages more nuanced theoretical and practical consideration of nature-health relations.

In this article, we review work done in recent decades to better characterize the health benefits of contact with nature. We do not cover this body of work comprehensively, but instead we focus on nature as represented by aspects of the physical environment relevant to planning, design, and policy measures that target broad segments of urban populations. We touch on clinically oriented work on contact with nature in therapeutic contexts, but we do not discuss benefits of companion animals, which may be taken as representations of nature (42; however, see 6). Although the core ideas we discuss have a durable legacy in public health practice, the topic has not previously been the focus of an *Annual Review of Public Health* article (however, see 44, 80).

Below, we examine the concept of nature, consider reasons for the current expansion of research, and provide a "review of reviews." We then review research on pathways involving air quality, physical activity, social cohesion, and stress reduction. Finally, we discuss methodological issues and priorities for future research.

DEFINING "NATURE"

In an objective sense, "nature" as used here refers to physical features and processes of nonhuman origin that people ordinarily can perceive, including the "living nature" of flora and fauna, together with still and running water, qualities of air and weather, and the landscapes that comprise these and show the influence of geological processes. As such, "nature" overlaps substantially with "natural environment," an environment with little or no apparent evidence of human presence or intervention, and the two terms have been used interchangeably.

In practice, however, much research does not accept exclusion of the artificial as a basis for defining nature or natural environment. The nature of interest is often situated in built environments, as with indoor plants and street trees. Similarly, allotment (or community) gardens and urban parks comprise natural features, appear natural, and provide opportunities to engage with and follow natural processes, but they are typically designed, constructed, regulated, and maintained. Research has also acknowledged that a person may experience nature as such when viewing natural elements or landscapes from a building or vehicle, in photographs and films, or in virtual reality setups.

The term "urban nature" is instructive. It admits the presence of nature even in those human environments that some consider the antithesis of the natural. Yet, just as it puts the urban and natural together, it also sets them apart. It exemplifies how contacts with nature in an urbanized

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society occur within a frame of reference shaped in an everyday life oriented in various ways to the society's urban circumstances.

The term "nature experience" is used in some segments of this research to emphasize the subjective perception and evaluation of relevant environmental features (67). It is, however, not a purely individual subjectivity, nor is it fixed. An individual's experience of nature occurs within and carries further the long-running exchange between the society and its environment (48).

Nature experience: the subjective experience of nature as such

In sum, although nature has a wide variety of objective referents, it is also experienced subjectively and is effective as a social construction (for further discussion, see 106). Accordingly, researchers represent nature with diverse physical and spatial variables, encountered in diverse activity contexts. Some also apply measurement, analysis, and design strategies to tap into the subjective experience of the environment. Because opportunities for contact with nature, ways of encountering nature, and experiences of nature vary across sociocultural contexts, researchers have examined variation in outcomes not only among individuals within given populations, but also across populations (108).

SOME REASONS FOR THE CURRENT RESEARCH EXPANSION

Growth in this field of research is shown clearly by the increase in publications. For example, a search in the Web of Knowledge on just one term, "greenspace and health," yielded 2 hits for 1990–1999, 34 for 2000–2009, and 45 from 2010 to June 2013.

Why is this expansion occurring? Motives for involvement in the field vary. Some work reflects concerns that urbanization, environmental degradation, and lifestyle changes are quantitatively and qualitatively diminishing possibilities for human contact with nature. For example, dense urban settings, if poorly designed (without accessible green space), may reduce opportunities for stress-reducing nature contact as well as increase exposure to environmental stressors (53). Other work considers nature as just one aspect of the physical environment that is potentially beneficial for health. For example, epidemic obesity in some countries has focused attention on sedentary lifestyles and environmental supports for physical activity, including but not limited to nearby parks (24). In general, the research aims to inform practical measures that directly or indirectly involve access to nature, including provisions for housing, transportation, and recreation.

Change in thinking about health has also enabled expansion of the research field. With the epidemiologic transition to chronic, lifestyle-related diseases as the major causes of mortality, biopsychosocial explanation (33) came to compete with the biomedical model, and constructs such as "psychological stress" and "social support" came into widespread use. This development has suited a field populated mainly by people trained in disciplines (e.g., human geography, environmental psychology, social epidemiology) and professions (e.g., outdoor recreation management, landscape architecture, urban forestry) that take interest in how people perceive, interpret, evaluate, and act on the environment. The conception of health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (138, p. 100) has also been influential for its heuristic value and as a basis for action. By acknowledging the positive, multidimensional character and subjective aspects of health, this concept supports the involvement of a wide variety of actors in efforts to understand and support health, including but not limited to those trained to treat symptoms of ill-health (132). Research in the field accordingly represents health in many ways, not only with regard to forms of morbidity (86), causes of mortality (94), and longevity (119) but also with regard to self-reported health (26) and diverse intermediate outcomes involving different pathways, such as beneficial change in emotional and physiological markers of stress measured during visits to natural areas (3, 49).

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Methodological and conceptual advances are also feeding the expansion of the field; old and new topics are being studied with a range of new tools. For example, beliefs about stress-reducing effects of park visits are widespread and long-standing (101), but experimental testing of such effects is a relatively recent activity (52, 125). These small-scale experimental demonstrations of pathway plausibility informed the first large-scale epidemiologic studies to assess associations between contact with nature and health (26, 87, 93). Those studies used resources and techniques that only recently became available. For example, they used land-use data extracted from satellite images with digital technologies to describe the spatial extent of different kinds of nature accessible to the given individuals and groups in their residential contexts.

Having considered some of the developments in societies, sciences, and professions that have motivated and enabled the recent expansion of this field, we turn now to examine the research in more detail, starting with previous efforts to review the literature.

REVIEW OF REVIEWS

Many review articles on nature and human health have been published in recent years. Assessing them is one means of summarizing the state of the field in terms of what is known and the quality of the research. In April 2013, we undertook a systematic search for reviews. We used Medline and all Web of Knowledge databases to identify peer-reviewed papers, sought nonindexed, non-peer-reviewed (gray) literature, and online reviews via Internet searches, and examined citation lists of already identified reviews. We included review articles or reports relevant to relationships between nature and human health and well-being. Inevitably, because the topic boundaries of nature and health are fuzzy, relevance was sometimes difficult to establish. For example, reviews on environmental correlates of physical activity often include access to urban parks or trails among many other environmental characteristics, but they may not focus on natural environments. We identified 59 relevant reviews at the time of the search (see **Supplemental Material**. Follow the **Supplemental Material link** from the Annual Reviews home page at **http://www.annualreviews.org**). Of the peer-reviewed articles, most appeared in journals concerned with public health or environmental planning.

Supplemental Material

The reviews varied considerably in methodology and guiding aims. We observed three broad search-and-synthesis approaches: (*a*) narrative reviews, not clearly based on a systematic literature search ($n = 24$); (*b*) narrative reviews based on a systematic literature search or comprehensive case identification ($n = 13$); and (*c*) full systematic reviews based on an exhaustive literature search ($n = 22$). The reviews tended to have one of four general aims. First, systematic reviews sought to collate and synthesize all evidence for the effects of specified contacts with nature on specified markers of health (e.g., 2, 123). Second, summary reviews often aimed to introduce the field, explain its concepts and the mechanisms by which natural environments might affect health, and then set out some evidence for effects (e.g., 54, 89). Some were published as gray literature and had been commissioned by governmental or nongovernmental agencies. A third group included what might be labeled "flag-waving" reviews (e.g., 42, 95). These were aimed at introducing the topic to a new audience and were often relatively brief. Fourth, and fewer in number, were conceptual reviews, methodological reviews, or those proposing new theoretical perspectives (e.g., 8, 79).

Reviews also varied by the environments and/or pathways to health discussed. Physical activity had the most dedicated coverage as the focus of 18 reviews (e.g., 65, 90). Mitigation of poor air quality/urban heat problems and physiologically/psychologically restorative effects also had dedicated reviews (e.g., 12, 15, 19). Twenty-six of the reviews addressed multiple mechanisms. The reviews covered a wide range of natural features and environmental categories, including

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indoor plants (16), urban parks (90), and forests (22), but coverage was uneven. Urban parks were the most commonly considered setting. Two categories of environments were conspicuously underrepresented or absent; rural areas had just one review (41), and there were no review articles about gardens or allotments or community gardens other than those used for therapeutic purposes. Also, very few reviews focused on population subgroups. Children were the most commonly considered subgroup (e.g., 91, 96). We found no reviews dedicated to differences in relationships between nature and health by gender, ethnicity, or socioeconomic position.

Given this variety in method, aims, and focus, we find it interesting that there was strong agreement about the methodological state of the art. Reviews commonly concluded that the field remains dominated by observational study designs. Reviews agreed that too few primary studies have been carried out in a consistent and rigorous way to establish the causality of relationships between contact with nature and health. They agreed, too, that few primary studies have explored how effects may vary by population subgroup, by type of natural environment, or by type of contact with nature. Many reviews commented that consistent and objective measurement of both exposure to nature and health-related outcomes remains elusive.

We identified three weaknesses in the reviews with specific relevance to this field. First, search strategies did not always address the variety of environments or settings that count as "natural." It is necessary to enter multiple terms into the literature search to avoid missing important work. For example, urban parks may be described by one or more of park, green space, greenspace, green areas, open space, recreational space, natural space, natural environment, etc. Building a review of relevant literature on a search for "green space" or "park" alone, for example, is inadequate.

Second, reviews from individual-based disciplines such as psychology tended to ignore evidence from population-based disciplines such as epidemiology, and vice versa. A great strength of this field is that evidence exists to describe benefits of contact with nature at multiple levels, from laboratory experiments tracking individuals' physiological reactions to viewing natural scenes through to studies of differences in population mortality rates between more and less green cities. Each level and scale of study provides important components in understanding what contact with nature can and cannot do for human health.

Third, the variety of health outcomes used in primary studies was not well addressed. When reviews try to synthesize results from outcome measures that are sensitive to contact with nature in different ways, and for different durations, messages become clouded. The pooling of results from heterogeneous outcome measures may be motivated by a lack of multiple studies using consistent measures and study designs. However, failure to appreciate differences among outcome measures leads to mischaracterization of the evidence base. Heterogeneity in outcome measures used in primary studies perhaps explains the relatively small number of reviews that attempted a pooled analysis. The body of reviews consequently tells us little about effect size.

Overall, the reviews generally agreed that beneficial effects from contact with nature do occur and that these effects are plausibly connected to the mechanisms proposed in guiding theory. However, most of the evidence covered by the reviews related to intermediate health-related outcomes such as amount of physical activity, amount of social contacts, changes in physiological activity (e.g., cardiovascular, neuroendocrine, and musculoskeletal changes characteristic of stress reduction), changes in emotional states (e.g., increased happiness, decreased anger), and changes in cognitive capability (e.g., performance on standardized tests of executive attention) rather than to disease states or measures of mortality. The reviews found less evidence that traced full pathways from contact with nature, to measures reflecting the operation of the given mechanism(s), and on to longer-term outcomes. Thus, it is unsurprising that the reviews generally suggest that the evidence is not yet good enough to say when, where, and for whom given effects will occur or how large or long-lasting they will be.

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PATHWAYS THROUGH WHICH CONTACT WITH NATURE RELATES TO HEALTH

PM: particulate matter

VOC: volatile organic compound

Contact with nature may affect health via multiple pathways. Pathways that have received relatively large amounts of research attention involve air quality, physical activity, social cohesion, and stress reduction. We describe each of these pathways and indicate some of the complexities involved in drawing conclusions about its role, including variation in association across people, activities, and characteristics of the nature under study. The pathways emphasize different aspects of nature, as physical environment, as setting for (individual and social) behavior, and as experience. Contact with nature involves all these aspects, so multiple pathways are likely to be engaged simultaneously and affect one another, a point to which we return at the end of this section. The different pathways and possibilities for effect modification by individual or contextual variables are illustrated in **Figure 1**.

Air Quality

Trees, shrubs, and other vegetation may affect ambient air quality and, through it, human health and well-being. There are both positive and negative impacts. Trees and other vegetation may reduce levels of some pollutants, including gases and particulate matter (PM), but they may also contribute to air pollution by releasing hydrocarbons. Some trees and plants release pollen, aggravating allergies. Finally, trees improve air quality indirectly when they cool urban environments and reduce building energy demand.

Trees and other vegetation can reduce levels of gaseous air pollutants [e.g., ozone, oxides of nitrogen (NOx), oxides of sulfur] and PM (37). For gases, the primary mechanisms of action are uptake by leaf stomata, absorption, and adsorption to plant surfaces. PM removal occurs through deposition on leaves and other plant surfaces (7). However, most PM is resuspended to the atmosphere, washed off by rain, or dropped to the ground (100). Empirical studies (e.g., 34, 113) and modeling studies (e.g., 103, 120) suggest that urban tree canopy generally reduces air pollution levels by no more than a few percentage points, and often far less, although some results suggest more efficient removal of PM (59, 63) and certain volatile organic compounds (VOCs) (70). Because trees may reduce air movement, especially in restricted spaces such as urban "canyons," they may impede the localized dispersion of pollutants. Local factors such as the density, species composition, and age of the tree canopy, the concentration of air pollutants, and the length of the in-leaf season influence the extent of pollutant removal.

Plants may also affect indoor air quality—an important observation because people in developed nations may spend as much as 90% of their time indoors. VOCs such as benzene and formaldehyde may derive from furniture, carpets, cleaning agents, paint, and other sources. Indoor plants, especially such species as English ivy and spider plant, have been shown to reduce levels of many VOCs (81, 140). Bacteria in the soil may account for some VOC scavenging attributed to the plants (102).

In contrast to pollutant removal, trees can also be a source of hydrocarbons, including isoprene and terpenes, with considerable variation by species (9). These biogenic hydrocarbons may function as precursors of ozone and secondary organic aerosols (20, 74). Modeling studies have assessed the relative contribution of biogenic emissions to pollution levels (e.g., 112). Results vary depending on the species of trees in a canopy, local atmospheric chemistry (especially levels of other precursors, such as NOx), local weather, and other factors.

Trees, grasses, and other plants release pollens, which can aggravate allergies and asthma in susceptible people (18, 27). The culprits vary with geography but include ragweed, grasses (e.g., Timothy, Bermuda, bluegrass), and trees such as catalpa and walnut. In cities that have favored

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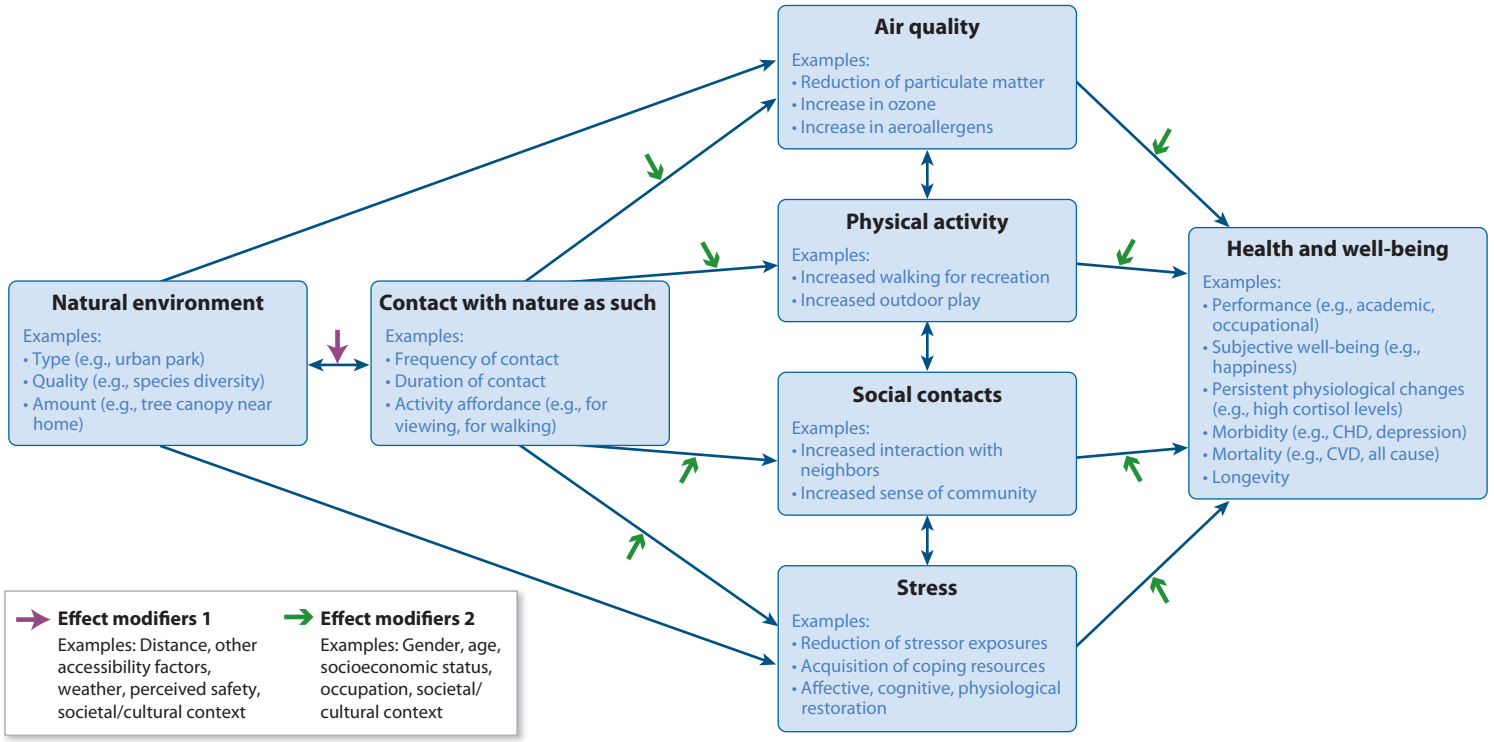


Figure 1

Some pathways through which the natural environment can affect the health of broad segments of populations. Four of the pathways go through contact with nature, whereas two others go directly from the natural environment to air quality and stress, respectively, implying that the natural environment may affect health without an individual or group consciously engaging with nature as such. Associations between variables at the different steps in a given pathway are subject to modification by characteristics of the people or the context. The two-headed arrow between the natural environment and contact with nature acknowledges that these are joined in a reciprocal relationship. The two-headed arrows between the variables designating pathways (air quality, physical activity, social contacts, and stress) also speak to their reciprocal relatedness; however, each may be related with all the others and not only with the one adjacent. Abbreviations: CHD, coronary heart disease; CVD, cardiovascular disease.

trees that are heavy pollen producers, the health impact may be especially significant (19). A study of African American and Dominican children in New York City found a small but significant association between tree canopy extent and asthma and allergic sensitization (83). Hence, in some circumstances, the allergenic role of trees may eclipse their ability to improve health by reducing air contaminants.

Vegetation, especially trees, may also indirectly benefit air quality. During warm weather, trees reduce summer air conditioning demand by shading and hence cooling buildings and through the cooling effects of evapotranspiration. This effect, in turn, reduces energy demand, which, in areas served by coal-fired power plants, reduces air pollution derived from coal combustion, though not necessarily at the same location (1). During cold weather, the reverse can happen. In a simulation study in Sacramento, trees reduced the need for cooling energy in summer about three times more than they increased the need for warming energy in winter (114). The monetary benefits of energy savings related to trees may exceed those of the pollutant removal (13).

The overall impact of vegetation on air quality is therefore a function of several processes, operating in opposing directions: hydrocarbon emissions, pollen production, pollutant uptake, and effects on energy demand. Careful selection of species, design of planting configurations with regard to wind, shade, and other impacts, and maintenance of urban vegetation can optimize the beneficial effects on air quality (30, 100).

Physical Activity

Physical activity promotes physical and mental health across the life span (10, 61). Recent evidence suggests that the health benefits of increased physical activity are largest among those who were initially doing the least (104). The outdoor environment may influence how physically active an individual is by offering suitable spaces for certain types of activities. It may also attract people outdoors because of the experiences it offers. Such outings ordinarily entail some form of physical activity, usually walking.

An important precondition for the use of natural environments for physical activity is individuals' (perceived) safety (62). Although there are possible negative effects associated with physical activity (e.g., sports injuries) as well as with being in a natural environment (e.g., Lyme disease from tick bites), most of these effects are not specific to physical activity in a natural environment.

Green space is only one part or aspect of the physical environment relevant for physical activity. Which environmental characteristics promote or hamper physical activity may depend strongly on the type of activity at hand (5). Three broad activity domains may be identified: work (including study), active transport (walking, cycling), and leisure (recreation, sport). Within the work domain, the greenness of the setting is thought to be of little importance for the amount of physical activity. The same is not true for active transport. Natural features may lead people to favor walking or cycling over other transport modes by making routes to destinations more attractive; however, distance to destination, availability of suitable infrastructure (e.g., sidewalks, bicycle paths), and safety are more important factors (55). The evidence for association between green space and active transport (walking and/or cycling) is mixed, and this heterogeneity has been well summarized by recent systematic reviews (40, 78). Reasons for (noncausal) negative associations may be that large amounts of green space tend to go together with (*a*) greater distances to destinations, (*b*) higher levels of car ownership, and (*c*) better availability and lower cost of car parking spaces near one's home (28, 55).

The importance of natural environments for fostering physical activity may vary by population subgroup. Children are perhaps the most commonly studied subgroup in this context, but again results are mixed. In one review (29), ~40% of the studies in which environmental characteristics

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were objectively measured showed park access or vegetation to be positively associated with children's physical activity levels; in the other 60% of the studies, no association was observed. A further systematic review (35) concluded that for (young) children the safety of the environment as perceived by their parents was an important moderating factor. Results from studies of older people are also mixed; two recent systematic reviews arrived at different conclusions. One (128) reviewed studies on the physical environment in general and concluded that there was no clear relationship between green space (and most other physical environmental characteristics) and physical activity of older people. The other specifically focused on green space, however, and it observed that seven out of eight studies showed a positive relationship between the greenness of the living environment and physical activity levels of older people (17). It also concluded that the perception of safety is an important moderating factor.

Relatively little attention has been paid to the relevance of specific environmental characteristics, such as the type of greenery or the quality of the open space. Results are again mixed. One study (46) concluded that very good access to large, very attractive public open space was associated with higher levels of walking. Another (56) by contrast observed no relationship between access to large, high-quality urban green spaces and recreational physical activity. A third study (25) observed a relationship of quality (but not quantity) of streetscape greenery with "green" activity, though not with total physical activity. Finally, recent results suggest that community gardening is associated with a lower body mass index (141).

Given that physical activity is assumed to be an important pathway joining nature with health, we find it surprising that few studies have formally investigated the extent to which any association between nature and health might be mediated by physical activity levels. Of four studies done (25, 88, 109, 118), only one (118) concluded that physical activity (more specifically recreational walking) was indeed an important mediator.

Finally, we note that most of the studies referred to in this overview have been cross-sectional in nature. Hence, the direction of observed relationships remains open to alternative explanations. For example, some people may choose a highly car-dependent (and presumably more green) living environment because they are not inclined to be physically active anyway (32).

Social Cohesion

Much as for physical activity, abundant research has documented positive associations between social relationships and health and well-being (57, 97). Such salutary associations have also been observed for positive relationships specifically within the neighborhood (110). A variety of terms have been introduced to reflect the potential value of social relationships in this context, including social capital, social support, social cohesion, and sense of community. Although these terms are often used interchangeably (4, 110), we draw a distinction here between social capital and social cohesion. Social capital comprises primarily those resources available to an individual through his or her social connections, which may be activated in times of need. In contrast, social cohesion refers to shared norms and values, the existence of positive and friendly relationships, and feelings of being accepted and belonging (cf. 36). We prefer to use the term social cohesion here because it is more a characteristic of neighborhoods than of individuals (4) and so more likely to be influenced by physical characteristics of the neighborhood, such as the availability and quality of green space and natural elements.

Unlike physical activity, the environmental correlates of social cohesion have received little research attention thus far. Generally, the few studies available suggest a positive relationship between social cohesion and natural environments (25, 38, 85, 118). Sugiyama et al. (118), for example, found perceived social coherence and local social interaction to be associated with the

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perceived greenness of the neighborhood. De Vries et al. (25) found an association between streetscape greenery and perceived social cohesion at the neighborhood scale, both for the quantity and, even more strongly, for the quality of greenery.

Social cohesion within a neighborhood does not lend itself to experimental research, which makes it difficult to determine whether relations with environmental features are causal. A few studies have, however, taken advantage of circumstances that likened a natural experiment. Researchers in Chicago (77) took advantage of quasi-random assignment of public housing residents to dwelling units in architecturally similar high-rise buildings with varying amounts of vegetation outside. They found a positive association between the presence of trees and grass on the use of common spaces and informal social contact with neighbors. Moreover, the relationship between greenery and social contacts appeared to be mediated by the use of the common spaces.

The research in Chicago (77) also showed that social contact was positively related to one's sense of safety. Subsequent studies showed that residents with more trees and grass around their buildings displayed less aggressive behavior, and their buildings were associated with fewer crimes (75, 76). More recent research suggests similar positive effects of greening vacant lots, especially a reduction in gun assaults and disorderly conduct (14).

Other attributes of the environment may moderate any association between natural features and social cohesion. Arguably, local parks must be well maintained and provide attractive recreational facilities to realize their full potential in developing social ties (71). Although green space generally is positively associated with feelings of safety, in dense urban areas enclosed green spaces may reduce such feelings (84). Similarly, trees in the public realm have been associated with reduced crime rates, but small trees on private lots have been associated with increased crime rates, presumably because these trees make it more difficult to observe criminal activity (31). Some natural settings, such as community gardens, incorporate social ties almost by definition. In one study, older allotment gardeners reported having more contacts with friends and felt less lonely than did nongardening neighbors in the same age category (131).

The question remains whether social cohesion, sense of safety, aggressive behavior, and crime rates mediate an eventual relationship between contact with nature and health. Results from a few cross-sectional studies bear on this point. One found that social cohesion partially mediated the relationship between perceived neighborhood greenness and mental health (118). Another concluded that feelings of loneliness and perceived shortage of social support partially mediated the relationship between the amount of green space within one kilometer and overall health (85). A third found that social cohesion mediated relationships between quantity and quality of streetscape greenery and both overall health and mental health (25). In contrast, Francis et al. (39) found neither sense of community nor social support to be an important mediator of the relationship between the quality of public open space and mental health. No studies were identified on mediation by aggressive behavior, fear of crime, and/or crime rates.

Stress Reduction

By helping people maintain adaptive resources needed to meet the demands of life, nature can reduce risk of illnesses involving chronic stress, as well as promote a range of intermediate outcomes such as increased subjective well-being. It can do so in two general ways. First, natural areas and features can reduce exposure to challenging environmental conditions by increasing distance to stressors and/or decreasing their perceptual salience. For example, green spaces between residences and heavily trafficked roads can reduce occupant noise annoyance (99), vegetation can conceal displeasing structures (115), and landscaping around housing can help residents maintain privacy and avoid feelings of crowding (23).

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Second, nature can help people restore their adaptive resources. Escape from physical and social stressors has long been described as an important motive for recreation in natural areas (58, 72). Nature's restorative quality does not, however, depend only on an absence of stressors; its restorative quality is also defined in positive terms. Another persistent motive for outdoor recreation has been appreciation of nature—for beautiful scenery, symbolic qualities, and other valued attributes (72). Push and pull motives also work in tandem in contexts other than outdoor recreation, notably the residential context. For example, residential location decisions commonly reflect efforts to both minimize stressful exposures and enhance access to restorative amenities, including green (or blue, i.e., water) areas (51).

ADD: attention deficit disorder

This motive combination appears in two theories about how nature can promote more rapid and complete restoration than other environments can. They offer contrasting views on how restoration can proceed once a person has gained psychological distance from threats and other demands. Psychoevolutionary theory holds that, for a person experiencing acute stress, nature contact can very rapidly evoke positive affect, which in turn blocks negative thoughts and feelings and fosters reduction of physiological activation (126, 127). Evolution purportedly conserved this functional aesthetic response because more rapid recovery from acute stress would have helped proto-humans better prepare for the next survival task. In contrast, attention restoration theory holds that effortless attention engaged by intrinsically interesting aspects of nature enables rest for a fatigued neurocognitive inhibitory mechanism engaged when willfully directing attention (67, 68). People must inhibit task-irrelevant stimuli as they direct their attention at work and in many other circumstances. Fatigue of this directed attention capability occurs commonly, undermines effective action, and can increase susceptibility to stress (68).

Informed by one or both of these theories, true and quasi-experiments done in laboratory and field settings have assessed diverse affective, cognitive, and physiological effects of more and less natural comparison conditions, realized over varying but generally brief time spans after a naturalistic or experimental induction of a need for restoration. Published studies generally report some restorative advantage of nature, and by 2004, reviewers had judged the evidence for restorative effects of nature to be strong (54). More recently, methodological heterogeneity led other reviewers (11) to include only 3–6 studies in quantitative syntheses for each of several outcomes. They concluded, nonetheless, that the available studies provided reliable evidence of reductions in self-reported anger, fatigue, anxiety, and sadness and an increase in feelings of energy. They also found tentative evidence of enhanced attention. Conclusions regarding physiological effects were limited by a lack of studies that had the desired design features. Studies done since that 2010 review have further expanded the body of experimental evidence in several directions: additional comparison conditions [e.g., more or less open vegetation (45); encountered in different ways, e.g., work site desktop relaxation packages (60)], alone or in company (64), and in additional subpopulations [e.g., children with attention deficit disorder (ADD) (121), with effects registered using additional measurement techniques (e.g., cortisol; 129)].

Other research assumes cumulative health effects of more effective restoration on many occasions over time. That work is bolstered by studies that situate repeated contact with nature into an ongoing process of self-regulation. Such studies recognize that some people learn that natural settings are more likely than other settings to be restorative. Over time, they apply this knowledge to better manage adaptive resources such as attentional capacity (69, 73, 116). When and how that learning begins remain understudied, but childhood experience appears influential for environmental attitudes measured in later life (133, 136). Some research does suggest that restorative childhood contact with nature can cumulatively provide benefits with far-reaching developmental significance. Contact with nature may for example improve attentional function in children with ADD (121) and enhance self-discipline in children without a diagnosis (122).

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Observational studies commonly cite nature's cumulative stress-reducing or restorative effects as one plausible pathway by which residential green space might affect perceived health (26, 87), diverse forms of morbidity (86), and death from circulatory disease and other causes (94). To date, however, most studies with individual data have not directly addressed a stress-reduction pathway owing to a lack of measures suitable for assessing mediation. One early quasi-experiment did however assess mediation with reference to attention restoration (76), and some recent surveys have begun to address this issue with self-report measures (25, 117). Another study has considered variation in the level of cortisol as a biomarker of chronic stress in members of a community sample living in more or less green circumstances (134); such a measure could serve tests of mediation of the effect of nature on stress-related illnesses.

Some studies have framed nature as a stress buffer, which has entailed estimating the interactive effect of stressful demands and access to nature on some health outcome. Several studies focused on nature in the residential context are illustrative. In a study done in rural New York state, conflicts at school experienced during the preceding three months were less strongly associated with psychological distress in children who had more nature in and around the home (135). In a Dutch study, the relationships between stressful life events in the previous three months and both health complaints and perceived general health were weaker among those with more green space within 3 km of the home (130). In an ecological study covering the population of England, high income deprivation had a weaker association with all-cause and circulatory disease mortality among people living in areas with relatively large amounts of green space (94).

In sum, substantial evidence speaks to the potential benefits of contact with nature for avoiding health problems traceable to chronic stress and attentional fatigue; however, the greater part of this evidence concerns the short-term restorative benefits of single encounters with or experiences in nature.

The Pathways Intertwine

Discussions of air quality, physical activity, social cohesion, and stress-reduction pathways emphasize different aspects of nature: as physical environment, as setting for (individual or social) behavior, and as experience. Contact with nature involves all these aspects, so multiple pathways are likely to be engaged simultaneously, as illustrated in **Figure 1**.

Most individual studies have focused on one particular pathway from nature to health, but some research has addressed combinations involving two or more of them. Much of this work has recognized links between physical activity and stress reduction. People commonly engage in physical activity not only or even primarily because it will serve their health in the long run, but also because it helps them to feel good in the short run, sometimes by reducing tension and stress. Conversely, people who want to enter a natural environment for restoration ordinarily must engage in some form of physical activity to do so. Accordingly, experiments have found "green exercise" more psychologically beneficial than the same exercise in settings with relatively little nature (92, 105). Thus, being active in natural settings may yield health benefits over and above the benefits of physical activity in other environments (for a meta-analysis, see 123). Conversely, a person walking or running along city streets may have to endure aversive conditions that reduce the benefits of the activity itself (49).

Multiple pathways may be purposefully combined in cultural practices that regularly bring people in contact with nature. For example, community gardening may promote social contacts during moderate physical activity that also supports restoration from stress associated with work or other demands. The Japanese practice of Shinrin-yoku, or forest-bathing, involves beliefs about the

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salutary values of certain substances in the air, and it entails behaviors that ordinarily promote stress reduction (e.g., distancing oneself from everyday demands, adopting a meditative stance) (124).

Some cultural practices that engage multiple pathways may however not be salutary for all population subgroups. For example, in some countries, many households maintain a simple, inexpensive leisure home in the countryside, to which family members ordinarily travel together during vacation periods; however, as a domestic setting, the leisure home may also impose unwanted demands and on some household members more than others. Swedish research found that, after several years of follow-up, employed men who owned a leisure home had lower odds of retiring early for health reasons (50); however, this prospective association did not hold for women. Indeed, among highly educated and highly paid women, the likelihood of early retirement for health reasons was greater if they also owned a leisure home. Other studies have also indicated a potential gender difference in the nature-health relationship (e.g., 107).

METHODOLOGICAL CHALLENGES

In addition to the usual methodological concerns in experimental and epidemiologic research, we must tackle a litany of specific methodological challenges if we are to develop our understanding of the degree to which, how, and under which circumstances contact with nature affects human health and well-being.

Measuring Exposure to Nature

Contact with nature challenges definition and control in field and laboratory experiments, and it is even more difficult to assess in free-living populations. Studies at population level typically assess exposure in one of three ways: assessments of exposure by how much nature there is in, or close to, the participants' area of residence; survey questions about how much time, and/or how often, people visit natural environments; and objective measures of contact via GPS (global positioning systems) technology. Each method has problems; that people live near natural spaces, report visiting them, or position themselves spatially within them does not mean that individuals actually have had contact with nature in a way that affects their health. None of these measures includes visual contact with nature from, for example, windows at home or in the workplace, which may also have beneficial effects (66). Furthermore, these measures typically miss fine details of exposure that may be important, such as the timing of exposure (e.g., for many environmental exposures, specific windows of vulnerability exist across the life span), the seasonality of exposure (e.g., the role of deciduous trees being in leaf), the quality of the nature (e.g., area in mature trees versus immature trees versus shrubs versus lawn), and the duration of exposure.

Measuring Outcomes

The other end of the equation between natural environment and health is the assessment of health itself. Plausible health impacts are varied and multiple, positive and negative, psychological and physiological, short term and/or long term. This plurality means many different health measures can be used, which, in turn, makes it difficult to achieve a coherent body of research. There is a particular challenge in bridging what we know about effects of contact with nature from small-scale, shorter-term experimental studies and what we might expect to observe as effects in the real world at the population level. For example, it is difficult to determine what the fall in blood pressure on viewing nature, established in experimental studies, might mean for rates of heart

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disease among regular visitors to national parks. There is no simple solution to this challenge and no one clearly superior set of instruments or measurements that are suited to use in all settings and studies.

Understanding Mechanisms

Understanding how any relationship between nature and health happens can aid interventions that promote possible benefits. It is also vital for specifying who might benefit most and least from the relationship. The challenge is that, as we have noted, the mechanisms by which nature might affect health are multiple and synergistic. They likely vary in significance within a single contact with nature, between contacts, across the life course, between population subgroups, between environment types and across cultures. Understandings of mechanisms being developed in the relatively controlled conditions of experiments should eventually help epidemiologists to form better hypotheses about the variation in associations they could expect at a population level.

Demonstrating Causality at a Population Level

Positive, short-term effects of contact with nature on affect, cognition, and physiology have been reasonably well established in laboratory and field experiments. However, cross-sectional designs still dominate studies of long-term health outcomes measured in populations. The vulnerability of these designs to confounding and reverse causality is a particular problem. The likelihood of contact with nature is strongly patterned by socioeconomic, ethnic, age, and cultural characteristics, which are, themselves, linked to health. Richardson et al. (108) provide a fine example of the potential for confounding factors to obscure relationships between green space and health at a population level.

Both experimental and longitudinal observational designs are potential routes to better evidence for a causal relationship among free-living populations. For studies of nature and health, however, both types of study impose specific challenges. Experimental studies at a population level are hard to perform. Manipulating environments or people is difficult and expensive. Scientists often must rely on public agencies or authorities to fund and deliver environmental changes, such as the creation of a new park or trail. It can also be difficult to establish and maintain control sites or populations, and opportunities to randomize the receipt of environmental interventions to different communities are rare. Useful results have emerged from quasi-experimental and before-after studies that capture some of the attributes of true experiments (14, 75). The timescale for effects is also often a constraint. Funding to follow-up intervention studies is rarely longer than 3–5 years, but effects at a population level (perhaps even intergenerational effects) may take longer to establish.

Research on nature and health has been undertaken within different scientific paradigms. Attitudes toward the level of proof for an association, indeed attitudes toward the very idea of "proof," vary between paradigms and are contested within them. Biomedical research, for example, often places great emphasis on low p-value thresholds for acceptance of an association. Frumkin (43) recently suggested, however, that the application of stringent p-value thresholds needs careful and explicit reconsideration in studies of nature and health. Moving from partial evidence to evidence-based recommendations regarding nature contact is a thorny problem.

For their part, existing panel or cohort studies that have good measures of health and well-being rarely also carry detailed information on contact with natural environments because this topic is relatively new to public health and epidemiology. Moreover, data sets that can also capture the change in or development of natural environments over time are rare.

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Effect Size

Evidence suggests that contact with nature has a small effect on health and well-being in comparison to structural characteristics such as income, employment, or education, and behavioral characteristics such as smoking. The signal-to-noise ratio in population-level studies is often small, and these studies need to be well designed and of sufficient power to identify any benefits. This does not mean that such studies are not worth doing, however; a small beneficial effect on a large number of people is a large contribution to population health (111).

PRIORITIES FOR FURTHER RESEARCH

Throughout this review we have identified issues that warrant further research, and in the previous section we have identified methodological challenges that must be met. Here, we try to highlight some specific priorities for the field.

First, we see a need to seek, create, and take opportunities for population-level experimental studies when they arise, within an understanding of their limits. Doing so will assist in demonstrating the degree to which nature-health relations have meaning for population health. We should also work to incorporate questions about contact with nature in ongoing longitudinal studies and ensure that high-quality data on change in type, quality, and availability of nature are maintained into the future and created retrospectively for the past. These additions would permit studies consistent with both cohort and life-course perspectives on relationships between nature and health.

Second, research on which types of nature are relatively effective for particular outcomes, and which qualities of those types are highly relevant, may be more fruitful when guided by theoretical ideas about why a particular type or quality of that type is likely to contribute to a particular pathway to health. Natural elements that are effective in improving air quality are not necessarily the same as those best suited to improving social cohesion in a neighborhood or to promoting psychological restoration.

Third, with specific regard to the stress pathway, much work remains to be done to rigorously assess theoretical claims regarding the components of experience that sustain attention restoration and stress recovery. To what extent, for example, are beneficial effects dependent on gaining psychological distance from stressful demands versus engaging with positive aspects of the nature encountered? This work will be aided by, among other things, further development of measures of perceived restorative quality in environments, and experimentation that more directly addresses the interplay of stress recovery, attention restoration, and other possible processes through which adaptive resources become renewed (cf. 49).

Fourth, if we acknowledge the competing priorities for funding and investment in health and health care, some research on nature and health might gain from a health economics perspective. If contact with nature is cost-effective as a means to protect and improve population health, it should be resourced and prioritized in preference to other approaches. Arguably, doing so requires knowledge not only about the economic significance of the health benefits generated, but also about the "doses" of nature needed to generate those benefits at the lowest possible cost. Discussions of dose, however, can entail a variety of problems, such as trivialization of contact with nature through neglect of long-term consequences of particularly powerful forms of contact (e.g., life-changing wilderness experiences). The dose metaphor therefore must be handled with care (137). As with other health-related issues, economic analyses must extend beyond health impacts to account for other benefits. For instance, an urban park may offer not only health benefits, but also benefits such as stormwater management and enhanced property values.

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Finally, variety between population subgroups in access to, use of, and responses to nature remains persistently underexplored. Spatial, social, economic, racial, cultural, and demographic differences in relationships between nature and health seem highly probable. It may be that relationships between nature and health are implicated in exacerbating or mitigating health inequalities between subgroups, for example. This potential should be thoroughly explored.

CONCLUDING COMMENTS

We have provided for a general public health audience an overview of research on how contact with nature relates to health in urbanized societies. We have not covered this body of work comprehensively, but instead have focused on nature as represented by aspects of the physical environment relevant to planning, design, and policy measures that target broad segments of urban populations, such as the availability of urban parks, the amount of green space in and near residential areas, and the preservation of peri-urban natural areas. Given our public health orientation, we have focused on the conditions of everyday life for the greatest part of the populations of interest. We consequently have hardly touched on the extensive literatures on wilderness experience (for reviews, see 72, 139) and contact with nature in the treatment and management of disability and illnesses such as depression (47) and breast cancer (21; see 2 for a review).

Despite such significant omissions, we trust readers will take away an appreciation not only of the diversity and complexity in forms of nature contact and potential benefits thereof, but also of the many challenges faced in characterizing those contacts and benefits. Taken together, the research reviewed does indicate that contact with nature can promote health. The evidence for some benefits, such as short-term restorative effects, is already quite strong. That said, nature contact should not be assumed always and automatically to be good for health; we have more to learn about for whom, when, how, and in which contexts it offers benefits.

Much also remains to be done to help those responsible for environmental policy, design, and management to make realistic assessments of what nature can and cannot do in their domain of activity. Part of this task involves explaining how health benefits might coincide (versus conflict with) other benefits, such as better stormwater management, species preservation, and carbon sequestration. If a particular form of nature contact shows small health benefits, interventions to promote it may still justify public investment if the health benefits combine with other benefits.

In closing, we recognize that many people speak of human-nature relations in moral/ethical and spiritual/religious terms with a view toward preservation of the natural environment. We respect such views. Our observations here regarding human health values should not be understood as the only or even the main bases for arguments regarding protection of habitats, species, and ecosystem integrity.

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[redacted] is a board member of the US Green Building Council and of the Children and Nature Network. [redacted] supervises a doctoral student funded by the UK Forestry Commission and has received research funding from the Forestry Commission in the recent past. The other authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Growing up green: a systematic review of the influence of greenspace on youth development and health outcomes



Abstract

Youth growing up in places with more greenspaces have better developmental outcomes. The literature on greenspace and youth development is largely cross-sectional, thus limited in terms of measuring development and establishing causal inference. We conducted a systematic review of prospective, longitudinal studies measuring the association between greenspace exposure and youth development outcomes measured between ages two and eighteen. We searched Cochrane, PubMed, CINAHL, Scopus, and Environment Complete, and included prospective cohort, quasi-experimental, and experimental studies on greenspace and youth development. Study quality was assessed using a 10-item checklist adapted from a previously published review on greenspace and health. Twenty-eight studies met criteria for review and were grouped into five thematic categories based on reported outcomes: cognitive and brain development, mental health and wellbeing, attention and behavior, allergy and respiratory, and obesity and weight. Seventy-nine percent of studies suggest an association between greenspace and improved youth development. Most studies were concentrated in wealthy, Western European countries, limiting generalizability of findings. Key opportunities for future research include: (1) improved uniformity of standards in measuring greenspace, (2) improved measures to account for large latency periods between greenspace exposure and developmental outcomes, and (3) more diverse study settings and populations.

Introduction

Healthy youth development is defined as a “lifelong adaptive process that builds and maintains optimal functional capacity and disease resistance”(1). Aspects of youth development are often divided into the following four dimensions: cognitive, social and



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emotional, speech and language, and fine and gross motor skills(2). Youth health outcomes (such as weight, obesity, and respiratory outcomes) are often metrics used to measure healthy youth development(3, 4). These pediatric health outcomes significantly influence child development as they influence long-term health outcomes throughout the individual's life course (3, 5). Throughout the course of history, interaction with nature has been believed to promote healthy development and improved quality of life among youth(6, 7). Although the impact of the built and natural environment on children and youth is not yet fully understood scientifically, evidence garnered thus far points toward the importance of childhood greenspace exposures(8).

Despite growing evidence suggesting that greenspace exposure promotes healthy youth development, the past five decades have seen stark declines in youths' interaction with nature(6). These declines in youth nature contact have been empirically measured in high income countries, however research suggest that the same phenomenon is occurring in low- and middle-income countries (LMICs)(6, 9). Researchers have attributed these declines to increased overscheduling of youths' time, interaction with technology, fear of stranger danger, and other factors(6). This phenomena has been coined as nature-deficit disorder and is believed to contribute to an array of physical, social, and emotional disorders (6, 10). To investigate the health impacts of nature, many scientists have used greenspace as an exposure to estimate individuals' relationship with nature (11), and over the past decade, a growing body of transdisciplinary research has linked greenspace exposure to a range of positive physical, cognitive, and socioemotional developmental outcomes in children and young people aged 2 to 21 (12–15). These studies suggest that interventions increasing greenspace exposure may constitute a sustainable approach to promoting youth cognitive(16), socio-emotional(17), language (18), and fine and gross motor development (19, 20). Additional studies suggest that greenspace promotes academic achievement for youth aged 8 to 15 (21–23), wellbeing for youth aged 9 to 15(24–26), and other health outcomes (such as cardiovascular health, obesity, and asthma) for children aged 18 years old or younger (27, 28).

While the evidence for greenspace exposure as a positive influence on youth development is promising, other reviews have identified that an overwhelming majority of these studies are cross-sectional (8, 29, 30). Cross-sectional studies are unable to capture the longitudinal nature of youth development and, therefore, inferences drawn from these studies are subject to biases (31–35). Ideally, research on greenspace exposure and youth development should shift from cross-sectional to longitudinal study designs—particularly prospective cohort, quasi-experimental, and experimental studies—in order to understand temporal relationships, latency periods, as well as multiple outcomes. To the best of our knowledge, the findings of published work that fit these study designs have not been consolidated into a single review. Therefore, in this systematic review, we followed PRISMA guidelines (Appendix 1) (36) to evaluate the current state of prospective longitudinal and experimental studies assessing the effect of greenspace exposure on youth development.

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Materials and Methods

Search strategy

We used MESH terms to encompass exposure to greenspace from childhood through adolescence, ages 2 through 18 (37). Though there is no universal definition, the Convention on the Rights of the Child states that a child is a human below the age of 18 years (38). While this review sought to examine the impact of greenspace on children and youth, studies with outcomes in children under age 2 were excluded as these years of infancy constitute a sensitive period when exposure to greenspace may produce distinct developmental outcomes requiring separate examination (39). The following combined search string was used to identify relevant studies from Cochrane, Web of Science, PubMed, CINAHL, Scopus, and Environment Complete databases from their earliest available dates through October 9th, 2020: ("green space" OR greenspace OR (green space)) AND (youth OR child* OR adolescent* OR pediatric) AND development. All search results were imported into the systematic review management software Covidence (40).

Screening

Covidence automatically removed duplicate articles found through the search process. Remaining abstracts were independently screened for relevance by two reviewers before passing on to the full text review. Discordant decisions were resolved by a third reviewer. The same double-voting process was followed during the full text review; two reviewers independently voted to include or exclude each study based on predetermined selection criteria. Conflicts during the full text review were discussed and decided on by the entire study team.

Selection criteria

Only studies including longitudinal data or experimental study designs were included. Longitudinal studies were defined as prospective cohort studies that did not measure greenspace exposure and a childhood developmental outcome at the same point in time. Experimental study designs were defined as 1) randomized controlled trials with true randomization or 2) quasi-experimental studies in which a greenspace intervention was tested among study groups without randomization. Studies were required to include prospective measurements of greenspace and developmental outcomes, defined as outcomes measured between ages 2 and 18, inclusive. Studies measuring outcomes related to physical health, cognitive functioning, socioemotional wellbeing, and mental health were included. Studies using the same datasets were included and treated as separate analyses.

Qualitative thematic analysis

Braun and Clarke's six-step method of qualitative analysis was used to generate outcome categories and organize studies into thematic bins, rather than using a pre-determined theoretical framework (41). This inductive approach was chosen to avoid biases and based on our guiding definition of youth development, given there is no current standard for this relatively novel field of research. During the full text screening, each reviewer independently recorded study outcomes. Two reviewers (N.S. and S.S.) conducted a preliminary analysis

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and generated broad categories to encompass study outcomes, which were discussed, revised, and finalized by the entire team. Once the thematic categories were identified, the authors conducted a brief literature review on the mechanism and pathways for each thematic category. Then, the same two reviewers independently classified all studies into the thematic bins. Four discrepancies in coding were resolved through discussion between all authors(42).

Quantitative quality assessment

Each paper was independently reviewed and scored according to a 10-item quality assessment checklist that was adapted from a previous systematic review of greenspace and health (43). We scored each study based on the following 10 domains derived from the previous systematic review: selection bias, inclusion bias, objectivity of outcome measure, derivation of greenspace measure, measurement of type of greenspace, measurement of use of greenspace, appropriate statistical methodology, effect size reporting, green space variable as main exposure, and level of exposure measurement (individual, ecological, or multi-level) (43). We adapted the quality levels of the initial assessment from a three-tier system (inadequate; adequate; insufficiently described) to a four-tier system (2—good; 1—moderate; 0—poor/unacceptable; N/A—insufficiently described) to align our study with best practices for systematic reviews in the environmental health sciences (43–45). Scores for each quality metric were averaged for studies in the same thematic bins, which were derived from the qualitative thematic analysis described in the prior section. Scores were then visualized in a heat map coded as follows: <1 was “poor or unacceptable” quality, 1 to <2 was “moderate” quality, and 2–3 was “good” quality.”

Results

Our literature search identified 1,471 potential studies, from which Covidence removed 755 duplicate articles (Figure 1). Initial abstract screening then eliminated 649 articles deemed irrelevant. Of the remaining 67 studies that underwent full-text screening, 28 were included in the final review (Appendix 2). From this final selection, we found 21 cohort studies (75%), 6 quasi-experimental studies (21.4%), and 1 cross-over experimental study (3.6%) evaluating the impact of greenspace exposure on youth development (Figure 2). All studies were conducted between 2014 and 2020. Figure 3 shows the global distribution of studies across 15 countries. Figure 4 depicts the age ranges captured by each study.

Each study operationalized greenspace exposure in at least one of four ways: (1) the distance to greenspace, (2) type of greenspace (e.g., parks, agriculture, gardens, etc.), (3) use of greenspace (e.g., walking, playing, etc.), and (4) frequency of exposure. Most studies (n = 21, 75%) focused on youths’ residential distance to greenspace. These studies spanned multiple greenspace measurement methodologies, the most common being the Normalized Difference Vegetation Index (NDVI), a graphical indicator of live green vegetation. Despite this shared NDVI measure, there were discrepancies in what was coded as greenspace. For example, some studies included agriculture as greenspace, while others did not. Only 7 (25%) studies included type of greenspace (e.g., agriculture, forest, etc.) in their analyses and 8 studies measured frequency and/or usage of greenspace exposure.

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Five developmental outcome categories were identified: cognitive and brain development (n = 6, 21.4%), mental health and wellbeing (n = 13, 46.4%), attention and behavior (n = 8, 28.6%), allergy and respiratory (n = 3, 10.7%), and obesity and weight (n = 2, 7.1%). Studies that fit into more than one developmental outcome category were double coded. One study focusing on eyesight development and spectacle use was coded as other, as it did not fit within the selected developmental categories. The results of a brief literature review on commonly proposed mechanisms explaining greenspace exposure's influence on these five developmental categories are presented in Table 1.

The overall quality of the reported studies was moderate, with almost all studies using adequate statistical methodology, adequately reporting effect sizes, and analyzing greenspace as the primary exposure of interest (Appendix 3). The results of the quality assessment by developmental category are visualized in Figure 5. Most studies had moderate risk of selection and inclusion bias, primarily due to small sample sizes or important differences between exposure groups. Outcomes were mostly self-reported across all the studies, introducing potential measurement bias. Greenspace measure derivation was adequately described in most studies, however almost none included details on the type or use of greenspace in their exposure measurement. Lastly, almost all the studies measured greenspace exposure at the ecological level, limiting the interpretation of findings at the individual level.

Cognitive and Brain Development

We identified six studies testing associations between greenspace exposure and youths' cognitive and brain development – four cohort studies(46–49), one quasi-experimental study(50), and one cross-over experiment(51). These studies were published between 2015 and 2019 and were all conducted in high-income European nations (Spain, Germany, the United Kingdom, Austria, Denmark, and the Netherlands). Sample sizes ranged from n = 47 to n = 2,539.

Three studies found a positive association between greenspace exposure and cognitive and brain development (46, 47, 51), while three studies found no association (48–50). Overall, greenspace exposure was positively associated with working memory(46), cognitive performance(51), and white and gray matter volume in several regions of the brain, including regions associated with cognitive performance and working memory (47, 52). One study with 2,593 participants found a positive association between greenspace exposure and cognitive development(46), while another study with 2,429 participants found no such health association(48), suggesting study power did not significantly impact findings. Additionally, the four cohort studies were evenly split between positive health associations(46, 47) and no health associations(48, 52), suggesting study design did not significantly influence findings.

The overall quality of the reported studies in this category was moderate. Several studies showed moderate risk of selection bias (12, 47, 49–51). One study showed moderate risk of inclusion bias (53) and one showed high risk of inclusion bias (46). Studies used a mix of objective and subjective measurements, including validated cognitive performance tests (46, 51), magnetic resonance imaging (47), and participant reports of academic grades (48). Greenspace exposure was well-defined across these studies, with four studies

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operationalizing greenspace exposure using the NDVI at the individual level (46–49) and two studies using natural features to classify different types of greenspaces (50, 51). Most studies did not, however, measure whether study participants used greenspace, likely biasing findings depending on how often children truly interacted with greenspace. Three cohort studies measured greenspace exposure only at baseline(46, 47), while the fourth cohort study measured greenspace exposure at multiple timepoints throughout the study (48, 49). Most studies controlled for age (46, 47, 50) and SES (46, 48, 49, 52). Notably, controlling for SES in one study attenuated positive health associations, pointing to SES as a potential confounder (49).

Mental Health and Wellbeing

We identified thirteen studies testing associations between greenspace exposure and youths' mental health and wellbeing – eight cohort studies(17, 54–60), four quasi-experimental studies(50, 61–63), and one cross-over experiment(51). These studies were published between 2014 and 2020, with twelve studies conducted in Europe (Denmark, Belgium, Austria, the United Kingdom, and the Netherlands) and one study conducted in the United States (Chicago, Illinois). Sample sizes ranged from 47 to 943,027.

All thirteen studies found positive associations between greenspace exposure and mental health & wellbeing. Overall, greenspace exposure was positively associated with improved prosocial behavior (58), mood (51), emotional resilience (17), and self-determination (63); increased happiness (54) and tonic vagal tone (50); decreased risk of developing schizophrenia (56); and lower incidence of psychiatric disorders, especially among adolescents and urban residents (57). Quasi-experimental studies found within-person improvements in mental health & wellbeing, consistent with findings from previous cross-sectional research (64). Between studies, age was not associated with mental health and wellbeing outcomes.

The overall quality of the reported studies was moderate. Seven studies showed moderate risk of selection bias (50, 51, 54, 57, 62, 63, 65) and one showed high risk due to small sample sizes (61). Three studies showed moderate evidence of inclusion bias (17, 50, 56) and two showed strong evidence (50, 61). These biases were most common in quasi-experimental studies. While most studies included objective measures of health (50, 51, 56–58, 65–67), many also used self-reported measures from study participants and their parents (17, 63, 67), increasing risk of self-reporting bias. Most studies also sufficiently defined their greenspace measure using descriptions of natural features (54, 62), a derivation of the NDVI (n = 4) (55–58), or other satellite imaging or land data (17, 59, 60). However, many did not measure frequency or type of greenspace use. Most studies adjusted for socioeconomic status at the individual level, often through a measure of household income or education(17, 54–60).

Attention and Behavior

We identified eight studies testing associations between greenspace exposure and youths' attention & behavior – five cohort studies (60, 68–71) and three quasi-experimental studies (62, 63, 72). These studies were published between 2017 and 2020, with six conducted

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in Europe (the United Kingdom, Spain, and Germany), one in Canada, and one in New Zealand. Sample sizes ranged from 100 to 66,283.

Seven studies reported positive associations between greenspace exposure and attention and behavior (60, 62, 63, 68, 69, 71, 72), while one study reported no association (70). Overall, greenspace exposure was associated with short-term prosocial behavior (62); improved self-determination (63), self-regulation (72), and attention (69); lower frequency of peer and conduct problems(60); and decreased odds of an ADHD diagnosis (68, 71). Based on the studies included in this thematic category, age was not significantly associated with attention and behavior outcomes.

The overall quality of these studies was moderate. Risk of self-reporting bias was low, as most outcomes were measured using validated questionnaires (70, 72), computer-based tests (69), ICD codes hospital, and pharmacy records (68, 69). Risk of inclusion bias was also low as most sample sizes were large and representative of source populations. Greenspace exposure was variably defined across these studies. Half used the NDVI (62, 68, 69, 72), while others used the Vegetation Continuous Fields (VCF), an indicator of tree canopy (73), and the Multiple Environmental Deprivation Index (MEDIx), an area-based measure capturing dimensions of health-related environmental drawbacks across the UK (71). Of the five cohort studies, three measured greenspace exposure at baseline, one obtained a ten-year average, and one measured greenspace at multiple time points throughout the study. All but one study (which measured pre- and post-scores) measured attention and behavioral outcomes at multiple timepoints. Only one study measured greenspace usage, and none measured frequency of greenspace use. All analyses were conducted at the individual level, and studies commonly measured greenspace exposure at the individual and ecological levels.

Allergy and Respiratory

We identified three cohort studies testing associations between greenspace exposure and youths' allergy and respiratory development (73–75). This category included studies on asthma, respiratory sinus arrhythmia (RSA), wheezing, allergic rhinitis eczema, and stress reactivity. These studies were published in 2019 and 2020, and were conducted in Europe (Italy, France, Slovenia, Poland, Portugal, and the Netherlands). Sample sizes ranged from 715 to 8063 youths.

All three studies had contradictory findings. One study found that youth living near greenspace had lower prevalence of asthma and rhinitis (74). Another study concluded that exposure to greenspace increased risk of allergic respiratory symptoms (73). The final paper reported no effects of exposure to neighborhood greenness on respiratory outcomes (76). A few possibilities may explain these differing results. First, these three studies were conducted in different countries that may have different proportions of urban, suburban, and rural youth. Additionally, different countries may have different levels of air pollution. An alternative explanation for the inconclusive results is the differences in participants' ages. Participants were measured at ages 4 and 7 in the study that found greenspace to lower the prevalence of asthma and rhinitis in youth (74), ages 3 through 14 in the study that found greenspace exposure to increase risk (73), and ages 11 through 22 in the study that found no significant results(76).

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The overall quality of the reported studies was low. One study's findings may be influenced by selection bias since the adolescent subsample (that scored higher on frustration and fearfulness, low scores on effortful control, higher scores on parental psychopathology, and living in a single-parent family) were slightly oversampled, which could have contributed to the null findings (75). Self-reporting bias was also likely present, as all studies predominantly used allergy and respiratory outcomes based on self-reported questionnaires; just one study used objective measures of RSA via stress reactivity, heart rate variability, and standardized residual RSA during speech to predict RSA during rest. Greenspace measures were clearly described and included information on the type of greenspace. Greenspace was operationalized using: the NDVI; the Species Richness Index (SRI) index, an indicator of the total number of species in a community; and as the percentage of neighborhood greenness and land cover exposures. The studies did not, however, include information on greenspace usage or frequency of greenspace use, which may have contributed to the inconclusive findings if children differentially used greenspace. For the three cohort studies included in our review, one study measured greenspace at baseline and two at multiple time points throughout the study. Every study measured outcomes at multiple timepoints. Analyses were conducted at the individual level and meaningful effect sizes with 95% confidence intervals were reported.

Obesity and Weight

We identified two cohort studies testing associations between greenspace exposure and youths' obesity and weight outcomes (77, 78). These studies were published in 2019 and 2020, with one conducted in the Netherlands and the other in the U.S. (Massachusetts). Both studies had large sample sizes (≥400 youths).

One study reported no significant findings after adjusting for confounders (i.e., age, sex, race, parental education/income etc.) (79). Notably, this study failed to collect baseline measurements of the outcome of interest, insulin resistance. The second study reported that shorter distances between youth's homes and greenspace were associated with significantly lower odds of youth overweight status. However, the closer a youth lived to an urban park, the higher the odds of being overweight (78). These contradictory findings may be due to measurement error, effect measure modification clouding a true association, or the absence of an association.

The overall quality of the reported studies was low, with evidence of selection and inclusion bias across studies. Both studies operationalized greenspace exposure using the NDVI at the individual level. One study measured greenspace exposure in addition to air pollution and traffic noise as exposure measurements at the time of outcome measurement (78). Another study measured greenspace exposure at multiple time points prospectively(77). The greenspace exposure measures were well described and included information on type of greenspace with one study using Landsat satellite imagery as a proxy for estimating` NDVI(77). Neither study accounted for greenspace usage or frequency of greenspace exposure, which may have biased findings towards or away from the null. Obesity and weight were measured objectively through body mass index (measured by medical

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professionals) and insulin resistance (measurement of beta cell function via fasting glucose, insulin, and/or C-peptide concentration).

Other

One cohort study measuring the association between greenspace exposure and spectacles use as a proxy for myopia did not fit into the selected categories. The leading causal theory for this relationship asserts that sunlight exposure is causally linked with reduced spectacles use (80). This study, published in 2017, was conducted in Barcelona, Spain with a sample of 1,812 youth (81). Overall, the study found a 28% reduction in the likelihood of spectacles use per interquartile range increase in time spent in greenspace (81).

The study met all but three quality criteria: inclusion bias, objective outcome measurement, and measurement of type of greenspace. Threat of selection bias was minimal, as the schools selected for this study were socioeconomically representative of Barcelona's school-aged population. Inclusion bias, however, may have been present, as youths included in the longitudinal analysis were more likely to have parents of European ethnicity than of non-European ethnicity, relative to Barcelona's population. This study also exhibited risk of self-reporting bias due to spectacles use being measured through a questionnaire. Greenspace was operationalized using the NDVI and a questionnaire completed by parents determining how frequently youth used greenspaces. Spectacle use was measured twice – once at baseline, and once at the end of the three-year study period. Finally, the study controlled for important confounders, including age, sex, parental education (as a measure of socioeconomic status), preterm birth, and exposure to tobacco smoke during childhood. Effect sizes were reported with 95% confidence intervals.

Discussion

In this systematic review, we evaluated 28 longitudinal studies that assessed the relationship between greenspace and youth development. To our knowledge, this is the first review investigating longitudinal studies of youths' greenspace exposure and youth developmental outcomes. The studies demonstrated mixed results in terms of study quality as well as the direction and magnitude of associations between greenspace exposure and youth developmental outcomes. Our thematic analysis revealed the following categories of greenspace influence on youth development: cognitive and brain development, mental health and wellbeing, attention and behavior, allergy and respiratory, and obesity and weight. We present a summary of our findings for each thematic category in Table 2.

In our review, half of the studies in the Cognitive & Brain Development thematic category found no health association between greenspace and youth development, while the other half found positive health associations. For the studies included in the Cognitive & Brain Development thematic category, there were no specific association between age of exposure and direction (positive, negative, or null) of health associations. The leading mechanistic theory explaining how greenspace exposure impacts cognitive and brain development is the Attention Restoration Theory, which posits that greenspace exposure reduces the burden of mental fatigue and therefore yields positive cognitive and brain development(64, 82). A recently published systematic review supports this theory, suggesting that greenspace

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exposure has a positive impact on cognitive and brain development(64). One study from our review, conducted in Barcelona, Spain using MRI imaging of the brain, further supports this theory, finding that greenspace exposure was associated with increased white and gray matter volume in clusters of the brain associated with working memory and attention(47).

All studies in the Mental Health & Wellbeing category of this review found positive health associations. Age was not associated with mental health and wellbeing outcomes for the studies included in the Mental Health & Wellbeing thematic category. The primary biological theories explaining how greenspace exposure impacts mental health and wellbeing are the Attention Restoration Theory and Stress Recovery Theory(64, 82). The Stress Recovery Theory posits that humans evolved primarily in natural settings and, therefore, are physiologically and psychologically adapted to natural rather than urban settings(83). Thus, it follows that greenspaces reduce both physiological and psychological stress(83). The Stress Recovery Theory also states that stress reduction through greenspace is both a health benefit and a mechanism through which other health benefits may manifest(84). Many greenspace researchers use both the Attention Restoration Theory and Stress Recovery Theory to complement each other in discussing the health benefits of greenspace(64, 82).

All but one study (which found no health association) in the Attention & Behavior thematic category of this review found positive health associations. There was no evidence that children's age influenced the relationship between greenspace exposure and attention and behavior outcomes. The predominant theory explaining the association between greenspace exposure and children's attention & behavior is the Attention Restoration Theory(85, 86). One landmark study – not included in this review because of its cross-sectional study design – found that youth have better attention and behavior in green settings and that youth with more green play areas have less severe symptoms of attention deficit disorder(85). This study suggested that greenspace access may serve as an alternative or supplement to current pharmaceutical-focused treatments, which often have their own side effects(85).

Most studies in Allergy & Respiratory thematic category found positive health associations, with only one study finding no health association. The current evidence on the association between greenspace exposure and youth allergy and respiratory outcomes is inconclusive(11). Typically, air quality is higher in natural settings and rural areas than in urban settings, resulting in lower prevalence rates of allergies and related respiratory issues in natural and rural areas(11). Thus, it is believed that greenspace may be better for youth allergy prevention and respiratory development. However, the interaction of greenspace and respiratory health is more complex in urban settings(11). Some studies have found that urban greenspace improves air quality and is therefore beneficial for youth respiratory health(87, 88), while other studies have found that exposure to urban greenspace may exacerbate asthma symptoms due to allergens (such as pollen and fungi)(89). For the studies included in this thematic category, younger children (ages 4 to 7) found positive health associations to greenspace, younger to "mid-aged" children (ages 3 to 14) found negative health associations, and older children (aged 11 through 22) found no health association. These age-related differences in the influence of greenspace on Allergy & Respiratory health outcomes is supported by a large literature base suggesting that younger children are more

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susceptible to environmental health exposures(90–92). Specifically, studies have found that early life environmental exposures significantly increase or decrease the risk of asthma later in adolescence (93, 94). Therefore, it is logical that the studies in this thematic category that included younger children found health associations, whereas the study of older children found no health association. We hypothesize that children in the study that found positive health associations between greenspace and allergy/respiratory outcomes benefited from the improved air quality. In contrast, children in the study that found negative health associations to greenspace may have had higher exposures to allergens.

One of two studies in the Weight & Obesity thematic category found positive health associations between greenspace and youth development, while the other half found no health association. For the studies included in the Weight & Obesity thematic category, there was no evidence that age influenced the relationship between greenspace exposure and this developmental outcome. Current evidence suggests an inverse association between greenspace exposure and being overweight or obese through the following pathways: reduction of negative environmental exposures that promote weight gain, reduction of stress and associated negative health behaviors (e.g., overeating, drinking, and smoking), and promotion of positive health behaviors (e.g., increased physical activity and social cohesion) (95–100). Although the current evidence base suggests that greenspace exposure reduces the risk of obesity, many findings are inconsistent and inconclusive(99–102).

Our review highlights several gaps in knowledge about how greenspace relates to youth development:

- Inconsistent measurements of greenspace exposure and confounders that complicate cross-study comparisons and meta-analyses.
- A dearth of studies conducted in low-income, non-White, and non-Western populations coupled with limited documentation of race and ethnicity.
- Inadequate longitudinal rigor to account for large latency periods between cumulative greenspace exposure and developmental changes in youth.

Thus, we propose the following research agenda for enhancing the evidence base of longitudinal studies on greenspace's influence on youth development:

1. Developing more rigorous and standardized measurements of greenspace

The current evidence base suggests inconsistent, yet promising, research findings on greenspace exposure and youth development(49, 79, 87, 103, 104). As demonstrated by this review's finding, many studies suggest that greenspace promotes healthy youth development. We hypothesize that discrepancies in research findings are partially due to inconsistencies in measurements of greenspace exposure and inconsistent control variables. These discrepancies are major threats to the validity of greenspace research.

Methods to operationalize greenspace exposure are imprecise; discrepancies in type, use, and frequency of exposure create challenges in quantifying dosage of exposure(11, 15, 29). As seen in our review, types of greenspace exposure range from agricultural land to "untouched" nature, to urban tree coverage and more(11, 60, 63, 69, 105). While type of

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greenspace is commonly, but not always, accounted for in greenspace research, the use and frequency of interaction with greenspace is equally important, but is less often accounted for(11). Only eight studies in this review (29%) incorporated use and/or frequency of greenspace exposure, and many of those studies did not provide clarification on exposure type(51, 62, 63, 72, 81, 106). We would like to highlight one study from this review of 2,727 schoolchildren in Barcelona, Spain that used both questionnaire and GIS data to assess greenspace exposure, thus incorporating distance, use, and frequency of greenspace exposure(81).

Many studies did use NDVI data. The advent of NDVI data means that future studies will have a relatively long historical record of greenspace data to draw on in future studies of youth development. While NDVI is a cheap and accessible metric that would allow for strong historical record, it is important to note that the metric has been criticized for its inaccuracy and oversimplifications of types of greenspaces(107). Other, more accurate and detailed, metrics include the enhanced vegetative index, the moderate resolution imaging spectroradiometer (MODIS) NDVI, the MODIS leaf area index, and light detection and ranging (LiDar)(108).

Air pollution and health outcomes research has begun to overcome similar barriers to research(109). Current air pollution and health research have developed methods to generate person-specific assessments of air pollution exposure; however, there is limited research on the exposure's long-term health outcomes(109). The use of these person-specific exposure assessments can be adapted and applied to greenspace research for more precise measurements of greenspace exposure. However, it is important to consider who would be included in these studies, as the majority of current greenspace and youth development research focuses on white youth from high-income European countries. Greater specificity of greenspace measurement may cause greater selection bias and continue to limit generalizability to other populations. Thus, the tradeoffs between specificity of greenspace measurement and generalizability must be carefully weighed. Nonetheless, future longitudinal studies on greenspace and youth development must account for relevant dimensions of greenspace, namely distance, type, use, and frequency. The inconsistencies in *what* and *how* greenspace is measured and what confounders are controlled for lead to issues establishing causal links between greenspace exposure and youth developmental outcomes.

2. Diversifying sample population

As shown in Figure 3, research on greenspace and youth development has mostly been conducted in high income nations. Most of the studies included in this systematic review come from Europe, with a few originating in the United States, New Zealand, and Canada. With the exception of the United States (which only has 2 studies), all countries have some form of universal healthcare and have low levels of income inequality(110). Furthermore, only 3 of the 28 studies (11%) reported ethnic and racial demographics. Based on the countries in which these studies were conducted, we assume that most studies that did not include racial demographics had primarily White participants. This is a major threat to external validity, as racial minorities have been documented to have poorer access to greenspace, and therefore, less likely to receive the health-promoting effects

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of greenspace(111–113). Thus, more studies that include non-White populations and report racial and ethnic breakdowns are essential to propel the field forward.

This gap in research is detrimental to greenspace and youth development research as there are complex interactions between SES and access to greenspace. People enjoy living near greenspace and therefore, it has become an expensive luxury(114). Thus, in many countries with inequitable access to greenspace (such as the U.S.) certain communities have less access to greenspace due to historic housing policies and green gentrification (gentrification due to new greening efforts)(111). Additionally, poorly maintained greenspace has been shown in some communities to increase crime and drug violence, and therefore may be feared by the community(115). This complex interaction of social, environmental, and health factors needs to be accounted for in future greenspace and youth development research.

While many of the papers in this study statistically controlled for SES, more rigorous measures are needed to better understand the relationships between SES, greenspace, and youth development. SES is a complex confounder and encompasses both individual/household measures (such as household income, occupation, and education attainment) and more ecological measures (such as neighborhood poverty rate and average household income). Most studies included in this review controlled for a proxy of SES; however, this may be insufficient to understand the complex relationship between SES, greenspace, and youth development(116–119). Ideally, more experimental studies should be conducted to better understand whether, and to what extent, SES interacts with the association between greenspace and youth development.

In addition, no studies from this review were conducted in LMICs. Thus, the current evidence base cannot be generalized to LMICs, where basic needs may be less easily attained. Additionally, different cultures and countries have different views and uses of greenspace and nature contact(120–122). Thus, limiting studies to high-income countries prevents us from understanding the meaning and influence of greenspace in different social fabrics. It is important to note that there are great disparities in access to greenspace in LMICs, where non-white and low-income people live in dense urban centers with limited access to greenspace(123). More research must be conducted in LMICs to better understand how greenspace influences youth development in these settings. Would the youth development benefits be the same in LMICs? Or would other sociocultural factors influence these findings?

3. A push for more longitudinal studies, specifically RCTs

Of the 716 potential studies in this systematic review, only about 4% were longitudinal studies of greenspace and youth development. Of these, just 6 were quasi-experimental studies and 22 were cohort studies. Moreover, many studies failed to collect baseline measurements or measured exposure and outcome at the same time. This lack of methodological rigor may compromise the reliability of longitudinal associations between cumulative greenspace exposure and subsequent changes in developmental outcomes among youth. Our search strategy for this systematic review did not yield any RCTs, despite RCTs being regarded as the gold standard for determining causality(124). Although our

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search did not yield any RCT that evaluated the effect of greenspace on youth development, RCTs that assess the effects of greenspace on other health outcomes have been published previously(125, 126). For example, one study in Philadelphia, conducted an RCT on 110 vacant lots (greening 37, cleaning up trash in 36, and no intervention in 37) and found that adults living near the greened vacant lots had improved mental health outcomes(125). Similar rigorous research methods could be applied to greenspace exposure and youth development research to establish causal relationships.

Strengths and limitations—To our knowledge, this study is the first to evaluate solely longitudinal and experimental studies of greenspace exposure and youth development outcomes, thus making this systematic review a critical step in establishing causal links between greenspace and youth development. Another strength includes the use of an expert research informationist in determining the six databases used in this study and crafting a search algorithm. Other strengths include unrestricted publication dates for articles, a unique mixed-methods approach to systematic review, and the use of a peer-reviewed 10-item quality assessment for greenspace measures.

However, this study is not without limitations. First, all non-English studies were excluded from this systematic review and, therefore, we may have missed important scientific findings in other languages. The search terms may not have been exhaustive as development encompasses a vast set out of outcomes and greenspace may have been labeled otherwise. Another limitation is that due to the inconsistencies of greenspace exposure measures and differing outcomes, we were unable to conduct a meta-analysis(43). Lastly, this systematic review only focused on peer-reviewed journal articles to ensure quality of papers; important and relevant findings may be available elsewhere.

Conclusion

This systematic review evaluated the current evidence base of prospective, longitudinal and experimental studies on the effects of greenspace exposure on youth developmental outcomes. The 28 studies selected in this review suggest that overall, greenspace may promote positive youth development. More longitudinal studies, specifically RCTs, are warranted to establish this causal relationship. Additionally, future studies should include more rigorous and consistent measures of greenspace exposure and diversification of sample populations.

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[redacted]

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Data Availability

The data used during the current study are available from the corresponding author on reasonable request.

Appendix 1: PRISMA Report Checklist

#	Item	Guidance	On page #	Author Comments
Title				
1	Title	Identify the report as a systematic review, or systematic review and meta-analysis, as appropriate.	1	**Growing up green: a systematic review of the influence of greenspace on youth development and health outcomes**
Abstract				
2	Structured summary	Provide a structured summary including, as applicable: • Background; • Objectives; • Data sources; • Study eligibility criteria, participants, and interventions; • Study appraisal and synthesis methods; • Results; • Limitations; conclusions and implications of key findings; • Systematic review registration number.	2	Background: Youth growing up in places with more greenspaces have better developmental outcomes. The literature on greenspace and youth development is largely cross-sectional, thus limited in terms of measuring development and establishing causal inference. Objective: We conducted a systematic review of prospective, longitudinal studies measuring the association between greenspace exposure and youth development outcomes measured between ages two and eighteen. Data sources & Study eligibility criteria, participants, and interventions: We searched Cochrane, PubMed, CINAHL, Scopus, and Environment Complete, and included prospective cohort, quasi-experimental, and experimental studies on greenspace and youth development. Study Appraisal and synthesis methods: Study quality was assessed using a 10-item checklist adapted from a previously published review on greenspace and health. Results: Twenty-eight studies met criteria for review and were grouped into five thematic categories based on reported outcomes: cognitive and brain development, mental health and wellbeing, attention and behavior, allergy and respiratory, and obesity and weight. Seventy-nine percent of studies suggest an association between greenspace and improved youth development. Limitations, conclusions, and implications of key findings: Most studies were concentrated in wealthy, Western European countries, limiting generalizability of findings. Key opportunities for future research include: (1) improved uniformity of standards in measuring greenspace, (2) improved measures to account for large latency periods between greenspace exposure and developmental outcomes, and (3) more diverse study settings and populations. Systematic review registration number: N/A
Introduction				
3	Rationale	Describe the rationale for the review in the context of what is already known.	4	Ideally, research on greenspace exposure and youth development should shift from cross-sectional to longitudinal study

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				designs – particularly prospective cohort, quasi-experimental, and experimental studies, as these studies are better able to establish causality. To the best of our knowledge, the findings of published work that fit these study designs have not been consolidated into a single review. Therefore, in this systematic review, we evaluate the current state of prospective longitudinal and experimental studies assessing the effect of greenspace exposure on youth development.
4	Objectives	Provide an explicit Population-Intervention-Comparator-Outcome-Study Design (PICOS) or Population-Exposure-Comparator-Outcome-Study Design (PECOS) statement as appropriate, detailing the following in relation to the research questions being asked: • Participants • Interventions / Exposures (as appropriate) • Comparisons • Outcomes • Study design	4	Therefore, in this systematic review, we followed PRISMA guidelines (Appendix 1) (36) to evaluate the current state of prospective longitudinal and experimental studies assessing the effect of greenspace exposure on youth development.
Methods				
5	Protocol and registration	Indicate if a review protocol exists, if and where it can be accessed (e.g. web address), and registration information including registration number (if available).	N/A	
6	Eligibility criteria	Specify study characteristics (e.g. PICOS/PECOS, length of exposure) and report characteristics (e.g. years considered, language, publication status) used as criteria for eligibility, giving rationale.	5–6	Only studies including longitudinal data or experimental study designs were included. Longitudinal studies were defined as prospective cohort studies that did not measure greenspace exposure and a childhood developmental outcome at the same point in time. Experimental study designs were defined as 1) randomized controlled trials with true randomization or 2) quasi-experimental studies in which a greenspace intervention was tested among study groups without randomization. Studies were required to include prospective measurements of greenspace and developmental outcomes, defined as outcomes measured between ages 2 and 18, inclusive. Studies measuring outcomes related to physical health, cognitive functioning, socioemotional wellbeing, and mental health were included.
7	Information sources	Describe all information sources (e.g. databases with dates of coverage, contact with study authors to identify additional studies) in the search, and date last searched.	5	The following combined search string was used to identify relevant studies from Cochrane, Web of Science, PubMed, CINAHL, Scopus, and Environment Complete databases from their earliest available dates through October 9th, 2020: (“green space” OR greenspace OR (green space)) AND (youth OR child*

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				OR adolescent* OR pediatric) AND development.
8	Search	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	5	The following combined search string was used to identify relevant studies from Cochrane, Web of Science, PubMed, CINAHL, Scopus, and Environment Complete databases from their earliest available dates through October 9th, 2020: ("green space" OR greenspace OR (green space)) AND (youth OR child* OR adolescent* OR pediatric) AND development.
9	Study selection	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	5–6	*Screening* Covidence automatically removed duplicate articles found through the search process. Remaining abstracts were independently screened for relevance by two reviewers before passing on to the full text review. Discordant decisions were resolved by a third reviewer. The same double-voting process was followed during the full text review; two reviewers independently voted to include or exclude each study based on predetermined selection criteria. Conflicts during the full text review were discussed and decided on by the entire study team. *Selection criteria* Only studies including longitudinal data or experimental study designs were included. Longitudinal studies were defined as prospective cohort studies that did not measure greenspace exposure and a childhood developmental outcome at the same point in time. Experimental study designs were defined as 1) randomized controlled trials with true randomization or 2) quasi-experimental studies in which a greenspace intervention was tested among study groups without randomization. Studies were required to include prospective measurements of greenspace and developmental outcomes, defined as outcomes measured between ages 2 and 18, inclusive. Studies measuring outcomes related to physical health, cognitive functioning, socioemotional wellbeing, and mental health were included. Studies using the same datasets were included and treated as separate analyses.
10	Data collection process	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	6–7	*Qualitative thematic analysis* Braun and Clarke's six-step method of qualitative analysis was used to generate outcome categories and organize studies into thematic bins, rather than using a pre-determined theoretical framework (44). This inductive approach was chosen to avoid biases and based on our guiding definition of youth development, given there is no current standard for this relatively novel field of research. During the full text screening, each reviewer independently recorded study outcomes. Two reviewers (N.S. and S.S.) conducted a preliminary analysis and generated broad categories to encompass study outcomes, which were discussed, revised, and finalized by the entire team. Once the thematic categories were identified,

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				the authors conducted a brief literature review on the mechanism and pathways for each thematic category. Then, the same two reviewers independently classified all studies into the thematic bins. Four discrepancies in coding were resolved through discussion between all authors(45). *Quantitative quality assessment* Each paper was independently reviewed and scored according to a 10-item quality assessment checklist that were adapted from a previous systematic review of greenspace and health (41). We scored each study based on the following 10 domains derived from the previous systematic review: selection bias, inclusion bias, objectivity of outcome measure, derivation of greenspace measure, measurement of type of greenspace, measurement of use of greenspace, appropriate statistical methodology, effect size reporting, green space variable as main exposure, and level of exposure measurement (individual, ecological, or multi-level) (41). We adapted the quality levels of the initial assessment from a three-tier system (inadequate; adequate; insufficiently described) to a four-tier system (excellent; medium; poor/unacceptable; insufficiently described) to align our study with best practices for systematic reviews in the environmental health sciences (41–43). Scores for each quality metric were averaged for studies in the same thematic bins, which were derived from the qualitative thematic analysis described in the following section. Scores were then visualized in a heat map coded as follows: lower 10th percentile was “poor” quality, 50th percentile was “moderate” quality, and 90th percentile was “good” quality.
11	Data items	List and define all variables for which data were sought (e.g., PICOS/PECOS, funding sources) and any assumptions and simplifications made.	Appendix 2	Title, author, year, country, study design, sample size, participant age range, race reporting, green space measure, outcome of interest, outcome data source/collection method, other variables included in model, and key findings were extracted from each study.
12	Risk of bias in individual studies	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	6–7	We scored each study based on the following 10 domains derived from the previous systematic review: selection bias, inclusion bias, objectivity of outcome measure, derivation of greenspace measure, measurement of type of greenspace, measurement of use of greenspace, appropriate statistical methodology, effect size reporting, green space variable as main exposure, and level of exposure measurement (individual, ecological, or multi-level).
13	Summary measures	State the principal summary measures (e.g., risk ratio, difference in means).	N/A	Did not conduct a meta-analysis
14	Synthesis of results	Describe the methods of handling data and combining results of studies, if done, including	N/A	Did not conduct a meta-analysis

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		measures of consistency (e.g., I^2) for each meta-analysis.		
15	Risk of bias across studies	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	21	• Inconsistent measurements of greenspace exposure and confounders that complicate cross-study comparisons and meta-analyses. • A dearth of studies conducted in low-income, non-White, and non-Western populations coupled with limited documentation of race and ethnicity. • Inadequate longitudinal rigor to account for large latency periods between cumulative greenspace exposure and developmental changes in youth.
16	Additional analyses	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	N/A	
Results				
17	Study selection	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, illustrated with a PRISMA flow diagram.	7	Our literature search identified 1,471 potential studies, from which Covidence automatically removed 755 duplicate articles (Figure 1). Initial abstract screening then eliminated 649 articles deemed irrelevant. Of the remaining 67 studies that underwent full-text screening, 28 were included in the final review (Appendix 2).
18	Study characteristics	For each study, present in a summary table the characteristics for which data were extracted (e.g., study size, PICOS/PECOS, follow-up period) and provide the citations.	Appendix 2	Title, author, year, country, study design, sample size, participant age range, race reporting, green space measure, outcome of interest, outcome data source/collection method, other variables included in model, and key findings were extracted from each study.
19	Risk of bias within studies	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	Appendix 3	Full quality assessment table with risk of bias scores per dimension of quality.
20	Results of individual studies	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot (unless such a plot would be misleading)	No forest plot, heat map in Figure 5	
21	Synthesis of results	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	N/A	Did not conduct a meta-analysis.
22	Risk of bias across studies	Present results of any assessment of risk of bias across studies (see Item 15).	Figure 5	The quality assessment across studies by thematic category is presented in a heat map (Figure 5).

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23	Additional analysis	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	N/A	
Discussion				
24	Summary of evidence	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., researchers, users, and policy makers).	Table 2	Summary of associations between greenspace exposure and developmental outcomes.
25	Limitations	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	8–9 26	The overall quality of the reported studies was fair, with almost all studies using appropriate statistical methodology, adequately reporting effect sizes, and analyzing greenspace as the primary exposure of interest. The results of the quality assessment by developmental category are visualized in Figure 5. Most studies had moderate risk of selection and inclusion bias, primarily because of small sample sizes or important differences between exposure groups. Outcomes were mostly self-reported across all the studies, introducing potential measurement bias. Greenspace measure derivation was adequately described in most studies, however almost none included details on the type or use of greenspace in their exposure measurement. Lastly, almost all the studies measured greenspace exposure at the ecological level, thus limiting the interpretation of findings at the individual level. However, this study is not without limitations. First, all non-English studies were excluded from this systematic review and, therefore, we may have missed important scientific findings in other languages. The search terms may not have been exhaustive as development encompasses a vast set out of outcomes and greenspace may have been labeled otherwise. Another limitation is that due to the inconsistencies of greenspace exposure measures and differing outcomes, we were unable to conduct a meta-analysis(41). Lastly, this systematic review only focused on peer-reviewed journal articles to ensure quality of papers; important and relevant findings may be available elsewhere.
26	Conclusions	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	26	This systematic review evaluated the current evidence base of prospective, longitudinal and experimental studies on the effects of greenspace exposure on youth developmental outcomes. The 28 studies selected in this review suggest that overall, greenspace may promote positive youth development. More longitudinal studies, specifically RCTs, are warranted to establish this causal relationship. Additionally, future studies should include more rigorous and consistent measures of greenspace exposure and diversification of sample populations.
Funding				

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#	Item	Guidance	On page #	Author Comments
27	Funding	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	1	This work was partially funded by NIEHS T32 ES007322.

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Appendix 2.: Relevant study characteristics and primary findings from articles evaluating longitudinal association between greenspace exposure and youth development.

Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Green Schoolyards in Low-Income Urban Neighborhoods : Natural Spaces for Positive Youth Development Outcomes	Bates et al. (2018), USA	Cohort study	7025 (pre-k - 8th graders)	Y (44.7% African American, 39.2% Latino)	Green schoolyard renovation by the Space to Grow initiative	Social and physical health (a. children's behaviors on the schoolyard and b. changes in student safety, injuries, teasing/ bullying, and gang activity)	a. Child Activity Rating Scale, b. Retrospective self-administered surveys by caregivers and teachers	Race, income, and date of schoolyard renovation

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
The associations of air pollution, traffic noise and green space with overweight throughout childhood: The PIAMA birth cohort study.	Bloemsma et al. (2019), Netherlands	Cohort study	3,963 (0–17)	N	Greenness levels surrounding children's homes based on NDVI	Obesity	BMI (weight and height collected by medical professional)	Maternal and parental education, maternal smoking during pregnancy, parental smoking in child's home, and socioeconomic status

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Childhood exposure to green space – A novel risk-decreasing mechanism for schizophrenia?	Cherrie et al. (2019), Denmark	Cohort study	943,027 (10 years and older)	N	Satellite data from the Landsat program at 30 × 30 m resolution	Schizophrenia	Danish Psychiatric Central Research Register using ICD codes	Urbanization, age, sex, and socioeconomic status
A haven of green space: learning from a pilot pre-post evaluation of a school-based social and therapeutic horticulture intervention with children	Chiumento et al. (2018), Denmark	Quasi-experimental study	943,027 (10 years and older)	N	Mean green space and spatial heterogeneity of green space calculated from the NDVI obtained from 30 m resolution remote sensing images from the Landsat archive	Mental health and wellbeing	Schizophrenia and schizophrenia spectrum disorder (admitted to a psychiatric facility, received outpatient care, or visited a psychiatric emergency care unit with a diagnosis of schizophrenia (ICD10: F20 and equivalent ICD-8 codes) and schizophrenia spectrum disorder (ICD10: F20–F29 and equivalent ICD-8 codes).	Birth year, sex, and parents' education, income, and employment status
Green spaces and spectacles use in	Dadvand et al. (2017), Spain	Cohort study	1,812 (7–10 years)	N	Outdoor surrounding greenness at home and	Use of spectacles (proxy for myopia)	Questionnaire	Sex, age, parent ethnicity and indicators of

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
schoolchildren in Barcelona.					school and during commuting using NDVI and average annual time spent playing in green spaces based on questionnaires			socioeconomic status (educational achievement and employment status)
The Association between Lifelong Greenspace Exposure and 3-Dimensional Brain Magnetic Resonance Imaging in Barcelona Schoolchildren.	Dadvand et al. (2018), Spain	Cohort study	253 (7–10 years)	N	NDVI derived from RapidEye data, 5×5 resolution.	Regional differences in brain volume	Brain tissue measures/ volumes	Maternal education, Urban Vulnerability Index, sex, age; Inattentiveness, working memory, superior working memory
Lifelong Residential Exposure to Green Space and Attention: A Population-based Prospective Study.	Dadvand, et al. (2017), Spain	Cohort study	1,527 (0–7 years)	N	NDVI and Vegetation Continuous Fields (VCF)	Attention	Conners' Kiddie Continuous Performance Test (K-CPT) at 4–5 years and Network Task (ANT) at 7 years	Age, sex, preterm birth, maternal cognitive performance, maternal smoking during pregnancy, and exposure to environmental tobacco smoke

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Green spaces and cognitive development in primary schoolchildren	Dadvand, P. et al. (2015), Spain	Cohort study	2,593 (7–10 years)	N	NDVI in residence, commute, and school areas, as well as total greenness index (avg. of residential, commute, and school greenness).	Cognitive development (a. Working memory, b. Attention)	a. Computerized n-back test, b. Computerized attentional network test	Age, sex, indicators of socioeconomic status at individual and area levels (maternal education used as indicator of individual-level socioeconomic status, Urban Vulnerability Index used as indicator of area-level socioeconomic status); Traffic-related air pollution measured as a mediator
Association between exposure to the natural environment, rurality, and attention-deficit hyperactivity disorder in children in New Zealand: a linkage study	Donovah et al. (2019), New Zealand	Cohort study	49,923 (0–18 years)	N	NDVI and land-use data from Landcare Research New Zealand	ADHD	Hospital diagnosis or pharmacy records (two or more prescriptions for ADHD drugs)	Sex, ethnicity, mother's educational level, mother's smoking status, mother's age at parturition, birth order, antibiotic use, and low birthweight

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood	Engemann et al. (2019), Denmark	Cohort study	943,027 (10 years and older)	N	NDVI calculated using Landsat archive satellite imaging	Psychiatric disorders	Diagnosis upon visit to psychiatric ER, receiving outpatient psychiatric care, or admitted into a psychiatric facility with one of 18 psychiatric disorders	Age (different baselines for each gender), Urbanization, year of birth, gender, parents' education, parents' income, parents' employment status, parents' age, parents' previous psychiatric disorder diagnosis, and residential area socioeconomic status (at the municipal level)

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Association Between Childhood Green Space, Genetic Liability, and the Incidence of Schizophrenia	Engemann et al. (2020), Denmark	Cohort study	19,746 (10 years and older)	N	Mean yearly NDVI within square-shaped zones of 210 m × 210 for each year between birth and the 10th birthday	Schizophrenia	Danish Psychiatric Central Research Register and classified hierarchically as schizophrenia spectrum disorder (ICD-8: 295.x9, 296.89, 297.x9, 298.29–298.99, 299.04, 299.05, 299.09, 301.83; ICD-10: F20–29), affective disorder (ICD-8: 296.x9 [excluding 296.89], 298.09, 298.19, 300.49, 301.19; ICD-10: F30–39)	Parents' socioeconomic status and family history of mental illness
Associations between growing up in natural environments and subsequent psychiatric disorders in Denmark.	Engemann et al. (2020), Denmark	Cohort study	908,553 (10 years and older)	N	NDVI calculated using Landsat archive satellite imaging, then reclassified into urban, agricultural, near natural green space, and blue space.	Psychiatric disorders	Diagnosis upon visit to psychiatric ER, receiving outpatient psychiatric care, or admitted into a psychiatric facility with one of 18 psychiatric disorders	Air pollution, degree of urbanization, year of birth, parents' socioeconomic status (education, income, employment status), parents' history of mental illness, parents' age, and municipal socioeconomic status

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
The role of urban neighborhood green space in children's emotional and behavioral resilience	Flouri et al. (2014), England	Cohort study	6,348 (3–7 years)	N	Percentage of space within LSOA that was green based on 2001 Generalized Land Use Database (excluded domestic gardens)	Emotional and behavioral problem	Hyperactivity, emotional symptoms, conduct problems, and peer problems (Strengths and Difficulties Questionnaire (parent-reported))	Sex, ethnicity and age; mother's education and family structure; family socioeconomic disadvantage, life adversity, and neighborhood disadvantage
Early life exposure to green space and insulin resistance: An assessment from infancy to early adolescence.	Jimenez et al. (2020), USA	Cohort study	460 (1–13 yeras)	Y (75% white)	NDVI based on 30 m resolution Landsat satellite imagery	Insulin resistance	Insulin resistance (HOMA-IR)	Age, sex, race/ethnicity/ parental education/ household income/ neighborhood median household income
Outdoor air pollution, greenspace, and incidence of ADHD: A semi-individual study	Markevych et al. (2018), Germany	Cohortstudy	66,823 (10–14 years)	N	NDVI	ADHD	At least one ICD-10-GM F90 diagnosis by a child/adolescent psychiatrist, neuropediatrician, or psychotherapist	Sex, birth year
Residential and school greenspace and	Markevych et al.	Cohort study	2,429 (10–15 years)	N	Residential and school greenspace	Academic performance	Parent report at age 10 and child	Cohort (GINIplus observation,

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
academic performance: Evidence from the GINIplus and LISA longitudinal studies of German adolescents	(2019), Germany				measured by NDVI		self-report at age 15	GINIplus intervention, or LISA cohort), urbanicity, parent education level, single-parent status, income, sex, season during questionnaire response, type of school at age 15, time spent outdoors, time spent on a screen, and general mental health
Neighborhood greenspace and children's trajectories of self-regulation: Findings from the UK Millennium Cohort Study	Mueller et al. (2020), England, Scotland, Wales, and Northern Ireland	Cohort study	13,774 (3–7 years)	N	Multiple Environmental Deprivation Index (MEDIx)	Self-regulation independence and emotional dysregulation	Child Social Behavior Questionnaire	Neighborhood air pollution and deprivation, urbanicity, home physical environment, family background, maternal education and depression, and child-level covariates
Stress Response and Cognitive Performance Modulation in Classroom versus Natural Environments: A Quasi-Experimental Pilot Study with Children	Mygind et al. (2018), Denmark	Quasi-experimental study	47 (10–12 years)	N	Forested area (top of a grassy slope surrounded by trees on three perimeters overlooking a lake)	Stress response and cognitive performance	Heart rate variability (phasic vagal tone) (inter-beat R-R intervals with millisecond accuracy from Polar Team2 Pro chest-strapped HR monitors); Cognitive performance (d2 Test)	Age and gender
Influence of residential land cover on childhood allergic and respiratory symptoms and diseases:	Parmes et al. (2020), Italy, France, Slovenia and Poland	Cohort study	8,063 (3–14 years)	N	Land-cover exposures within a 500 m buffer of each child's residential address using the	Allergic and respiratory symptoms and diseases (wheeze, asthma, allergic	Parental questionnaires	Sex, age, BMI, maternal education, parental smoking, and parental history of allergy

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
Evidence from 9 European cohorts					Coordination of Information on the Environment program	rhinitis and eczema)		
Residential neighborhood greenery and children's cognitive development	Reuben et al. (2019), England and Wales	Cohort study	1,658 (5–18 years)	N	NDVI within a 1-mile radius of children's home	Cognitive development (overall cognitive ability at ages a. 5, b. 12, c. 18, and d. Executive function, working memory, and attention ability at age 18)	a. Shortened Wechsler Preschool and Primary Scale of Intelligence-Revised (two subtests used to measure crystallized ability and fluid ability), b. Shortened Wechsler Intelligence Scale for Children - IV (two subtests again to measure crystallized ability an fluid ability), c. Shortened Wechsler Adult Intelligence Scale - IV (two subtests measured crystallized and fluid ability), d. Cambridge Neuropsychological Test Automated Battery	Polygenic score for educational attainment, family socioeconomic status, neighborhood socioeconomic status, and sex
The role of public and private natural space in children's social, emotional and behavioural development in Scotland: A longitudinal study.	Richardson et al. (2017), Scotland	Cohort study	2,909 (4–6 years)	N	Area (%) of total natural space and parks within 500 m of child's home based on Scotland's Greenspace Map (park area, total natural space area, and private garden access)	Social, emotional and behavioral difficulties	Social, emotional, and behavioral difficulty scores (Strengths and Difficulties Questionnaire)	Sex, age, agê2, hours of screen time per day, household highest educational attainment, equivalized annual income and carer's mental component summary score (SF-12 questionnaire)

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
The neighbourhood natural environment is associated with asthma in children: A birth cohort study	Rufo et al. (2020), Portugal	Cohort study	1,050 (0–7 years)	N	Residential normalized difference vegetation index (NDVI) and species richness index (SRI)	Allergic diseases and asthma	Self-reported symptoms and history of medical diagnosed questionnaire based on the International Study on Allergy and Asthma Meeting standardized questionnaire completed by participant's legal guardians at follow-up	Sex, maternal history of asthma, household crowding, and maternal education
Purposeful Outdoor Learning Empowers Children to Deal with School Transitions	Slee et al. (2019), UK	Quasi-experimental study	100 (mean age 11)	N	Nature-based Outdoor Adventure residential program	Mental wellbeing and self-determination	Psychological well-being and self-determination (14-item Warwick-Edinburgh Mental Well-being Scale and 21-item Basic Psychological Needs Satisfaction in Life Scale and semi-structure interviews and informal discussions)	None
Self-regulation gains in kindergarten related to frequency of green schoolyard use	Taylor et al. (2020), Canada	Quasi-experimental study	385 (3–6 years)	N	Portion of the schoolyard that was replaced with softer surfaces (grass, sand, or mulch), planted young trees. Play elements such as a series of stumps for climbing and jumping, a low wooden platform for a stage, tires	Behavioral self-regulation	Child Behavior Rating Scale and The Head-Toes-Knees-Shoulders Task	None

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
					and sand embedded into a hillside for climbing, sandboxes, garden boxes, and semicircular seating areas were also installed.			
Residential landscape as a predictor of psychosocial stress in the life course from childhood to adolescence.	Van Aart et al. (2018), Belgium	Cohort study	172 (9–15 years)	Y (all children were white except for one of African origin)	Participant home's proximity to semi-natural, forested, and agricultural areas estimated based on satellite data from the European Coordination of Information on the Environment database	Childhood psychosocial distress (a. happiness, sadness, anger, and anxiousness, b. behavioral problems in the past 6 months, c. stress)	a. Likert scale of 1–10, b. Strengths and Difficulties Questionnaire completed by parents, c. hair cortisol	Distance to nearest major road with traffic counts, noise pollution, air pollution (predictors); Age, sex, socioeconomic status (covariates)
The impact of greening schoolyards on the appreciation, and physical, cognitive and social-emotional well-being of schoolchildren: A prospective intervention study	van Dijk-Wesselius et al. (2018), Netherlands	Quasi-experimental study	2031 (7–11 years)	N	Grassy hills, bushes, tree, tunnels made of tree branches, loose tree branches and garden-like parts	a. Physical activity, b. cognitive wellbeing (attention restoration), c. Social-emotional well-being (prosocial orientation, self-reported social behavior, and emotional functioning)	a. Accelerometers, b. Digit Letter Substitution Test and Sky Search task, c. Social Orientation Choice Card, subscale peer problems and prosocial behavior and Pediatric Quality of life scale	Gender and grade level
Reloading Pupils' Batteries: Impact of Green Spaces on Cognition and Wellbeing	Wallner et al. (2018), Austria	Cross-over experiment study	64 (16–18 years)	N	Inner urban small and heavily used park with a few trees and surrounded by heavily used streets and dense residential areas, a larger park with some tree clumps, or a larger broad	a. Cognitive performance, b. Wellbeing (recuperation, tension/ relaxation, state of mood, readiness for action, readiness for exertion, and alertness)	a. d2-R test (timed test of selective attention), b. self-condition scale by Nitsch	None

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Title	Author (year), country	Study design	Sample size (age)	Race and Ethnicity reported	Green space measure	Outcome(s) of interest	Outcome data source/collection method	Other variables included in model
					leaved forest with some scattered meadows and low visitor numbers			
The greener the better? Does neighborhood greenness buffer the effects of stressful life events on externalizing behavior in late adolescence?	Weeland et al. (2019), Netherlands	Cohort study	715 (11–16 years)	N	Percentage of neighborhood greenness	a. Externalizing problems, b. Respiratory sinus arrhythmia, c. Stress reactivity	a. Child Behavior Checklist Stressful life events, b. Heart rate variability in the high-frequency band (0.15–0.40 Hz), c. Standardized residual of RSA during speech (360 s) predicted by RSA during rest (25 min posttest (300 s))	Sex, age at baseline, externalizing behavior at baseline (CBCL), urbanization, and socioeconomic status

For studies that included both cross-sectional and longitudinal analyses, study characteristics from only the longitudinal analyses are depicted in this table.

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Appendix 3.: Present data on risk of bias of each study and outcome level assessment

TITLE	AUTHOR (YEAR), LOCATION	POPULATION - SELECTION BIAS (Are the individuals selected to participate in the study likely to be representative of the target population?)	POPULATION – INCLUSION BIAS (Is there evidence of bias in the percentage of selected individuals who provided data for inclusion in the analysis?)	OUTCOME MEASURE (Was the outcome objectively measured or self-reported?)	GREEN SPACE MEASURE – DERIVATION Was derivation of the green space variable well described?)	GREEN SPACE MEASURE – TYPE (Did the green space measure include information on type of green space?)	USE OF GREEN SPACE (Use of green space was measured and included in analysis)	STATI METH (Was a approp statisti metho used?)
Green Schoolyards in Low-Income Urban Neighborhoods: Natural Spaces for Positive Youth Development Outcomes	Bates et al. (2018), **USA**	Moderately representative (1)	Strong evidence of bias (0)	More subjective self-reported (0)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Approp metho
The associations of air pollution, traffic noise and green space with overweight throughout childhood: The PIAMA birth cohort study.	Bloemsma et al. (2019), **Netherlands**	Moderately representative (1)	Moderate evidence of bias (1)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Did not measure use of green space (0)	Approp metho
Childhood exposure to green space – A novel risk-decreasing mechanism for schizophrenia?	Cherrie et al. (2019), **Denmark**	Representative (2)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
A haven of green space: learning from a pilot pre-post evaluation of a school-based social and therapeutic horticulture intervention with children	Chiumento et al. (2018), **Denmark**	Not representative (0)	Strong evidence of bias (0)	More subjective self-reported (0)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Moder approp metho
Green spaces and spectacles use in schoolchildren in Barcelona.	Dadvand et al. (2017), **Spain**	Representative (2)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included moderate information on type of green space (1)	Measured use of green space adequately (2)	Approp metho
The Association between Lifelong Greenspace	Dadvand et al. (2018), **Spain**	Moderately representative (1)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure included adequate	Did not measure use of	Approp metho

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TITLE	AUTHOR (YEAR), LOCATION	POPULATION - SELECTION BIAS (Are the individuals selected to participate in the study likely to be representative of the target population?)	POPULATION – INCLUSION BIAS (Is there evidence of bias in the percentage of selected individuals who provided data for inclusion in the analysis?)	OUTCOME MEASURE (Was the outcome objectively measured or self-reported?)	GREEN SPACE MEASURE – DERIVATION Was derivation of the green space variable well described?)	GREEN SPACE MEASURE – TYPE (Did the green space measure include information on type of green space?)	USE OF GREEN SPACE (Use of green space was measured and included in analysis)	STATI METH (Was a appro statisti metho used?)
Exposure and 3-Dimensional Brain Magnetic Resonance Imaging in Barcelona Schoolchildren.						information on type of green space (2)	green space (0)	
Lifelong Residential Exposure to Green Space and Attention: A Population-based Prospective Study.	Dadvand, et al. (2017), **Spain**	Moderately representative (1)	No evidence of bias (2)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Did not measure use of green space (0)	Approp metho
Green spaces and cognitive development in primary schoolchildren	Dadvand, P. et al. (2015), **Spain**	Moderately representative (1)	Strong evidence of bias (0)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
Association between exposure to the natural environment, rurality, and attention-deficit hyperactivity disorder in children in New Zealand: a linkage study	Donovah et al. (2019), **New Zealand**	Representative (2)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood	Engemann et al. (2019), **Denmark**	Moderately representative (1)	No evidence of bias (2)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
Association Between Childhood Green Space, Genetic Liability, and the Incidence of Schizophrenia	Engemann et al. (2020), **Denmark**	Representative (2)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
Associations between growing up in natural	Engemann et al. (2020), **Denmark**	Representative (2)	No evidence of bias (2)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure included moderate	Did not measure use of	Approp metho

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TITLE	AUTHOR (YEAR), LOCATION	POPULATION - SELECTION BIAS (Are the individuals selected to participate in the study likely to be representative of the target population?)	POPULATION – INCLUSION BIAS (Is there evidence of bias in the percentage of selected individuals who provided data for inclusion in the analysis?)	OUTCOME MEASURE (Was the outcome objectively measured or self-reported?)	GREEN SPACE MEASURE – DERIVATION Was derivation of the green space variable well described?)	GREEN SPACE MEASURE – TYPE (Did the green space measure include information on type of green space?)	USE OF GREEN SPACE (Use of green space was measured and included in analysis)	STATI METH (Was a appro statisti metho used?)
environments and subsequent psychiatric disorders in Denmark.						information on type of green space (1)	green space (0)	
The role of urban neighborhood green space in children's emotional and behavioral resilience	Flouri et al. (2014), **England**	Representative (2)	Moderate evidence of bias (1)	More subjective self-reported (0)	Derivation of green space measure moderately described (1)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Moder approp metho
Early life exposure to green space and insulin resistance: An assessment from infancy to early adolescence.	Jimenez et al. (2020), **USA**	Moderately representative (1)	Strong evidence of bias (0)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Approp metho
Outdoor air pollution, greenspace, and incidence of ADHD: A semi-individual study	Markevych et al. (2018), **Germany**	Representative (2)	No evidence of bias (2)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Approp metho
Residential and school greenspace and academic performance: Evidence from the GINIplus and LISA longitudinal studies of German adolescents	Markevych et al. (2019), **Germany**	Representative (2)	No evidence of bias (2)	More subjective self-reported (0)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Approp metho
Neighborhood greenspace and children's trajectories of self-regulation: Findings from the UK Millennium Cohort Study	Mueller et al. (2020), **England, Scotland, Wales, and Northern Ireland**	Representative (2)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Approp metho
Stress Response and Cognitive Performance Modulation in Classroom	Mygind et al. (2018), **Denmark**	Moderately representative (1)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure moderately described (1)	Green space measure included moderate information	Measured use of green space	Approp metho

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TITLE	AUTHOR (YEAR), LOCATION	POPULATION - SELECTION BIAS (Are the individuals selected to participate in the study likely to be representative of the target population?)	POPULATION – INCLUSION BIAS (Is there evidence of bias in the percentage of selected individuals who provided data for inclusion in the analysis?)	OUTCOME MEASURE (Was the outcome objectively measured or self-reported?)	GREEN SPACE MEASURE – DERIVATION Was derivation of the green space variable well described?)	GREEN SPACE MEASURE – TYPE (Did the green space measure include information on type of green space?)	USE OF GREEN SPACE (Use of green space was measured and included in analysis)	STATI METH (Was a appro statisti metho used?)
versus Natural Environments: A Quasi-Experimental Pilot Study with Children						on type of green space (1)	moderately (1)	
Influence of residential land cover on childhood allergic and respiratory symptoms and diseases: Evidence from 9 European cohorts	Parmes et al. (2020), **Italy, France, Slovenia and Poland**	Representative (2)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Appro metho
Residential neighborhood greenery and children's cognitive development	Reuben et al. (2019), **England and Wales**	Moderately representative (1)	No evidence of bias (2)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Appro metho
The role of public and private natural space in children's social, emotional and behavioural development in Scotland: A longitudinal study.	Richardson et al. (2017), **Scotland**	Representative (2)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Appro metho
The neighbourhood natural environment is associated with asthma in children: A birth cohort study	Rufo et al. (2020), **Portugal**	Representative (2)	Strong evidence of bias (0)	More subjective self-reported (0)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Did not measure use of green space (0)	Appro metho
Purposeful Outdoor Learning Empowers Children to Deal with School Transitions	Slee et al. (2019), **UK**	Moderately representative (1)	No evidence of bias (2)	More subjective self-reported (0)	Derivation of green space measure poorly described (0)	Green space measure did not include information on type of green space (0)	Measured use of green space adequately (2)	Appro metho

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TITLE	AUTHOR (YEAR), LOCATION	POPULATION - SELECTION BIAS (Are the individuals selected to participate in the study likely to be representative of the target population?)	POPULATION – INCLUSION BIAS (Is there evidence of bias in the percentage of selected individuals who provided data for inclusion in the analysis?)	OUTCOME MEASURE (Was the outcome objectively measured or self-reported?)	GREEN SPACE MEASURE – DERIVATION Was derivation of the green space variable well described?)	GREEN SPACE MEASURE – TYPE (Did the green space measure include information on type of green space?)	USE OF GREEN SPACE (Use of green space was measured and included in analysis)	STATI METH (Was a appro statisti metho used?)
Self-regulation gains in kindergarten related to frequency of green schoolyard use	Taylor et al. (2020), **Canada**	Moderately representative (1)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure well described (2)	Green space measure did not include information on type of green space (0)	Measured use of green space adequately (2)	Appro metho
Residential landscape as a predictor of psychosocial stress in the life course from childhood to adolescence.	Van Aart et al. (2018), **Belgium**	Moderately representative (1)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Did not measure use of green space (0)	Appro metho
The impact of greening schoolyards on the appreciation, and physical, cognitive and social-emotional well-being of schoolchildren: A prospective intervention study	van Dijk-Wesselius et al. (2018), **Netherlands**	Moderately representative (1)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space moderately (1)	Appro metho
Reloading Pupils' Batteries: Impact of Green Spaces on Cognition and Wellbeing	Wallner et al. (2018), **Austria**	Moderately representative (1)	No evidence of bias (2)	Less subjective self-reported (1)	Derivation of green space measure well described (2)	Green space measure included adequate information on type of green space (2)	Measured use of green space adequately (2)	Appro metho
The greener the better? Does neighborhood greenness buffer the effects of stressful life events on externalizing behavior in late adolescence?	Weeland et al. (2019), **Netherlands**	Moderately representative (1)	Moderate evidence of bias (1)	Objectively measured outcome (2)	Derivation of green space measure moderately described (1)	Green space measure included moderate information on type of green space (1)	Did not measure use of green space (0)	Appro metho

Abbreviations:

NDVI	Normalized Difference Vegetation Index
RSA	respiratory sinus arrythmia

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SES	socioeconomic status
LMIC	low- and middle-income countries

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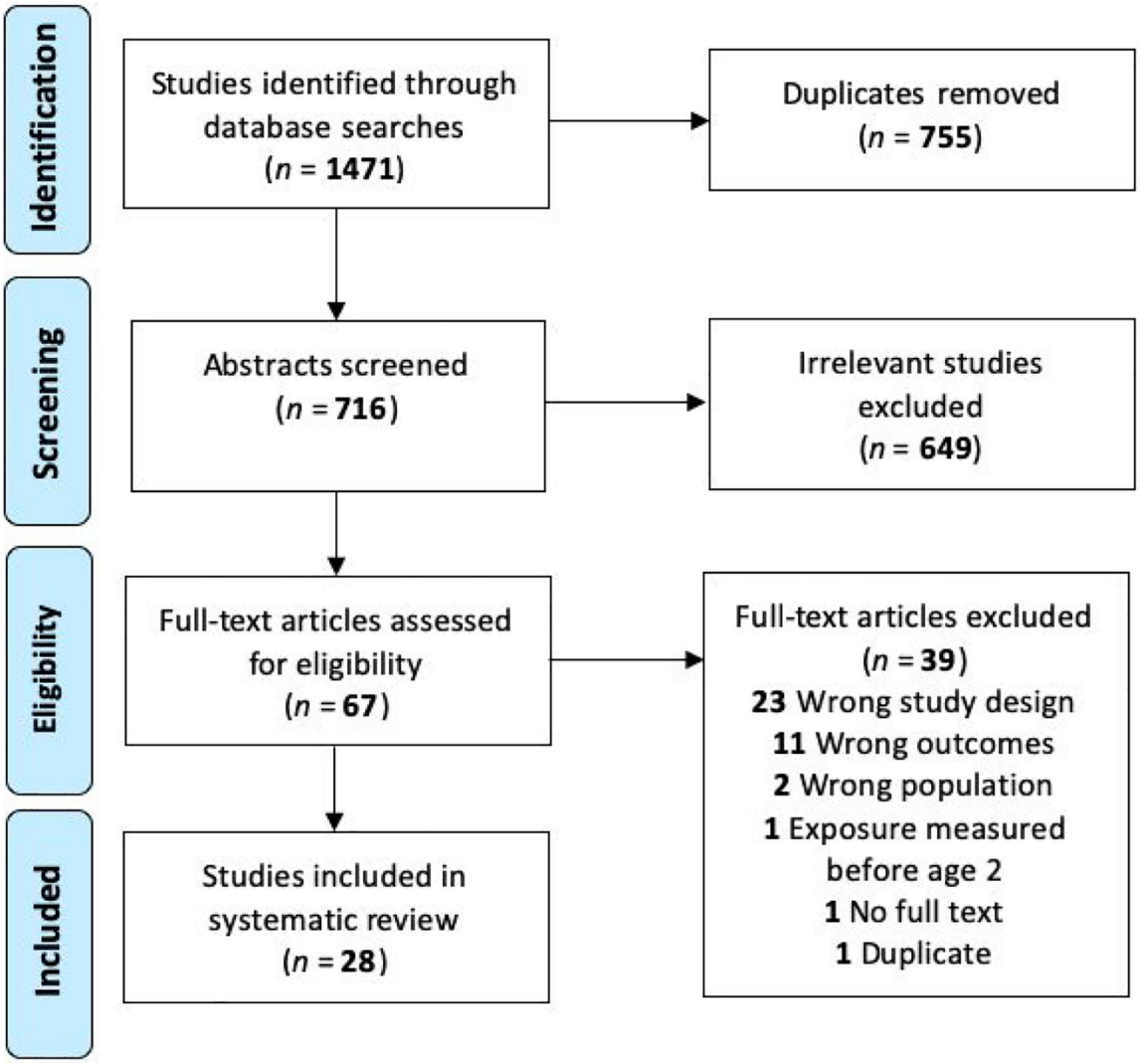


Figure 1.
Flow diagram of literature search, screening, and full-text review results.

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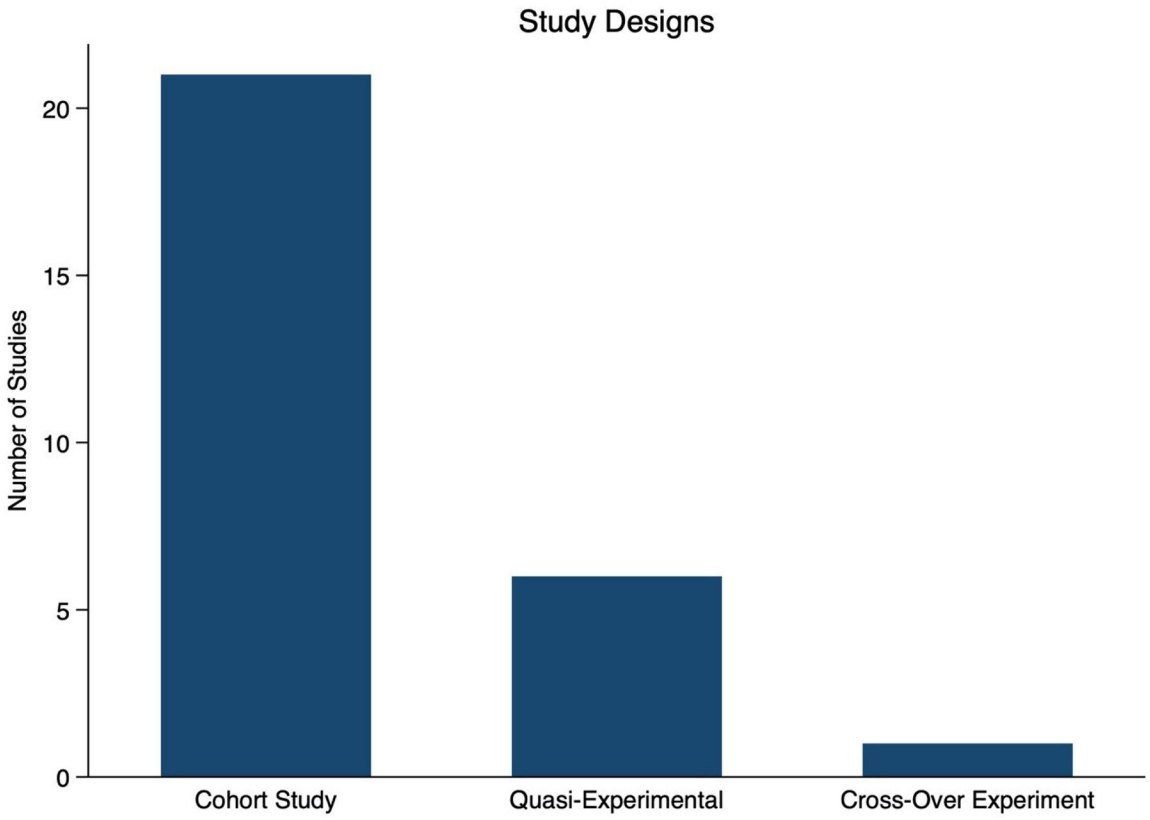


Figure 2.
Study design distribution in this systematic review.

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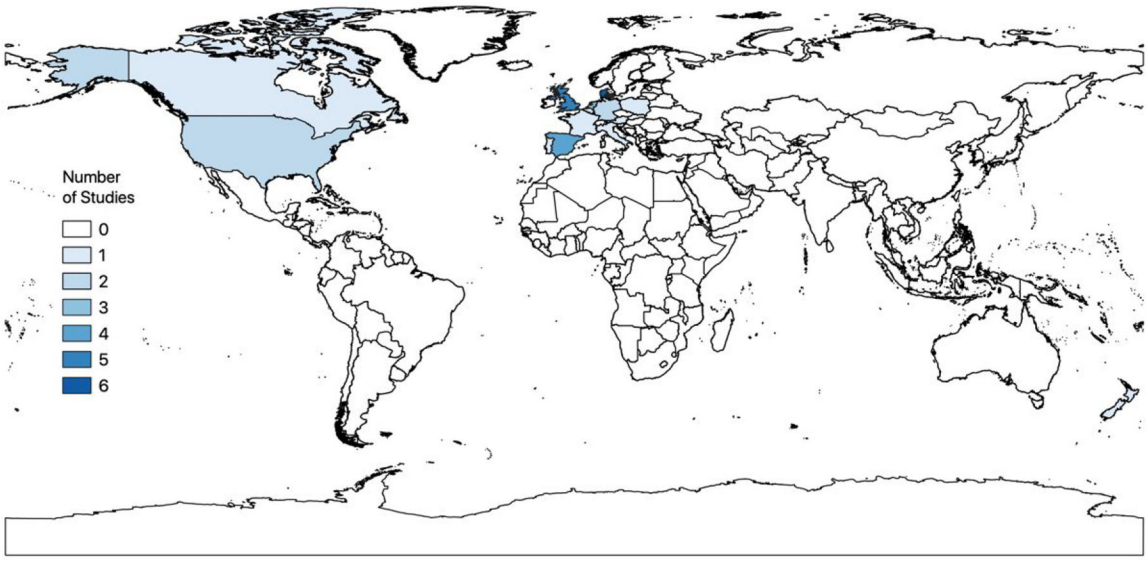


Figure 3.
Global distribution of longitudinal and experimental studies examining greenspace and youth development by country.

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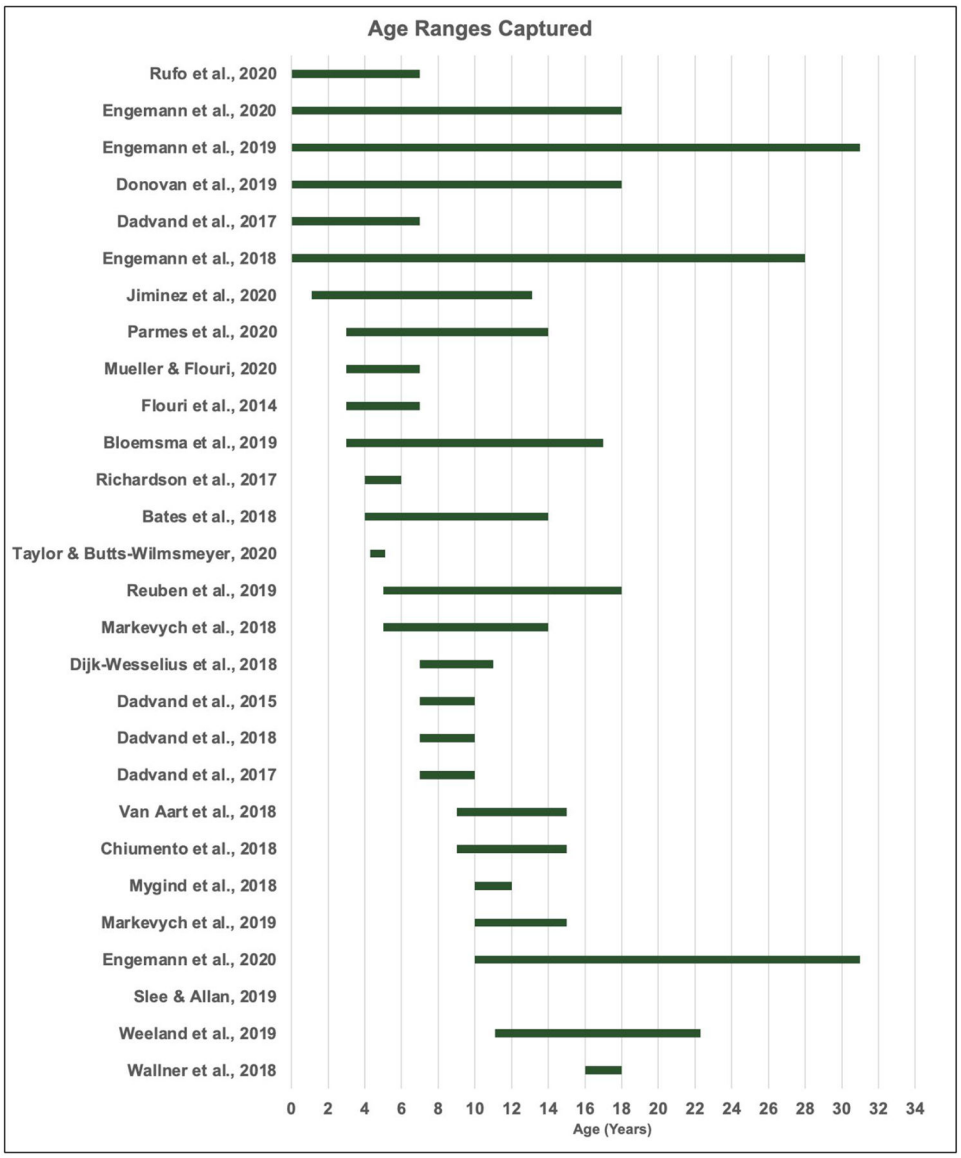


Figure 4.
Age ranges captured by each study.

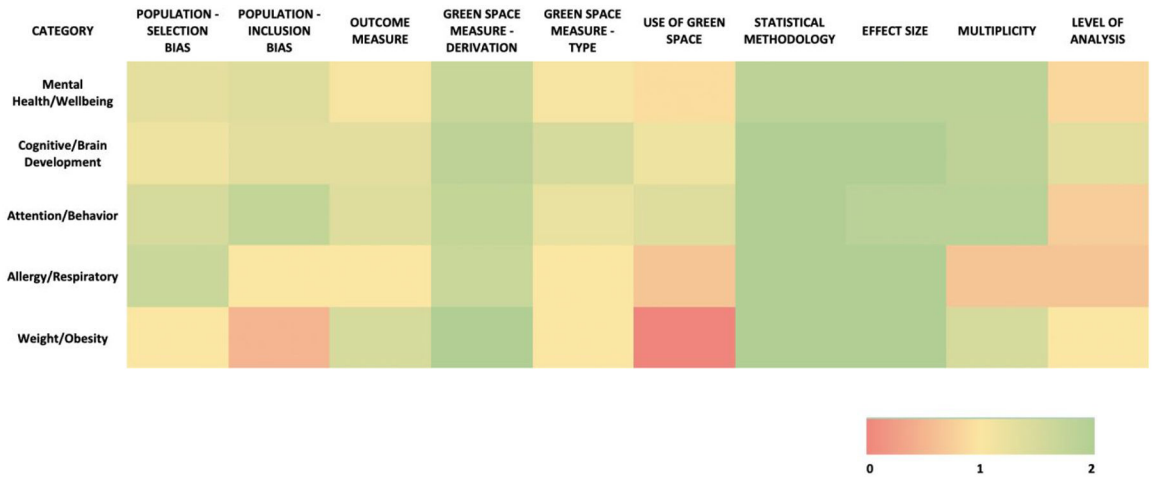


Figure 5.

Heat map of quality scores across developmental thematic categories. Scores were categorized as follows: 0= poor/unacceptable quality, 1= medium quality, 2 = excellent quality.

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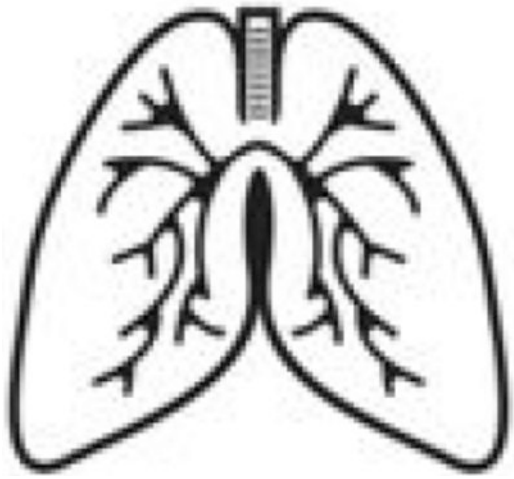
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Table 1.

Commonly proposed mechanisms linking greenspace exposure to youth development by health outcome categories.

Cognitive and Brain	
	Greenspace is thought to support cognitive integrity and healthy brain development because it engages the mind effortlessly, without demanding focused attention, and aids in recovery from ‘attention fatigue’, according to Attention Restoration Theory.
Mental Health and Wellbeing	
	Greenspace is thought to benefit mental health and enhance wellbeing through a variety of mechanisms: Natural settings are less mentally taxing and restorative, according to Attention Restoration Theory (see above); Humans are evolutionarily better adapted to natural rather than urban settings, according to Stress Recovery Theory; Greenspace is associated with healthier environmental conditions, such as lower temperatures, less air pollution and noise; Greenspace promotes physical activity; Greenspace increases and enhances social interactions.
Attention and Behavior	

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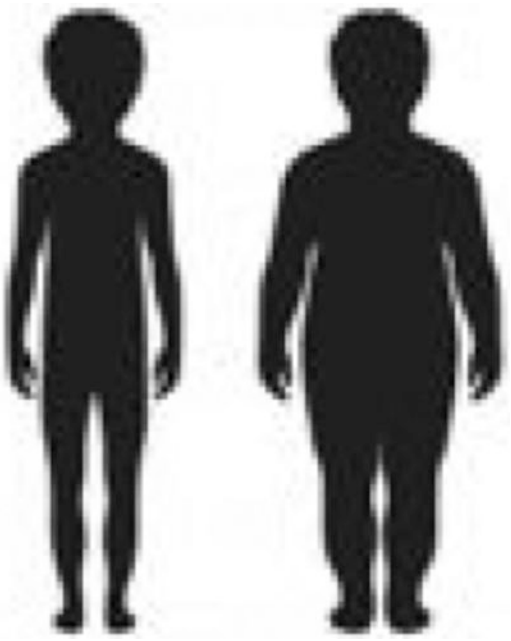
	Greenspace is thought to promote self-regulation and concentration among youth as it induces restful cognitive engagement, rather than focused attention, as proposed by the Attention Restoration Theory (see above).
Allergy and Respiratory	
	Greenspace is thought to influence respiratory health by improving air quality, supporting allergy prevention and respiratory development. However, exposure to urban greenspace may exacerbate asthma symptoms due to the proliferation of allergens.
Obesity and Weight	

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	Greenspace is thought to prevent overweight and obesity in children by reducing negative environmental exposures that promote weight gain, stress and associated negative health behaviors (e.g., overeating, drinking and smoking), and promoting positive health behaviors (e.g., increased physical activity and social cohesion).

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Table 2:

Summary of associations between greenspace exposure and developmental outcomes.

Developmental Outcome	Direction of Health Impact	Greenspace exposure was associated with…
Cognitive and Brain Development **(n=6 studies)**	Positive (n=3) No Association (n=3)	• Improved working memory. • Increased cognitive performance. • Increased white and gray matter volume in different regions of the brain, including regions associated with cognitive performance and working memory.
Mental Health and Wellbeing **(n=13)**	Positive (n=13)	• Improved pro-social behavior. • Improved mood • Improved tonic vagal tone. • Increased emotional resilience. • Increased self-determination. • Increased happiness. • Decreased risk of developing schizophrenia. • Decreased incidence of developing psychiatric disorders, especially among adolescents and urban residents.
Attention and Behavior **(n=8)**	Positive (n=7) No Association (n=1)	• Increased short-term pro-social behavior. • Improved self-determination. • Improved self-regulation. • Improved attention. • Lower frequency of peer and conduct problems. • Lower odds of an ADHD diagnosis.
Allergy and Respiratory **(n=3)**	Positive (n=1) Negative (n=1) No Association (n=1)	• Increased risk of allergic respiratory symptoms. • Lower prevalence of asthma and rhinitis.
Obesity and Weight **(n=2)**	No Association (n=1) Conflicting (n=1)	• Lower odds of being overweight. • Higher odds of being overweight in urban settings.
Other **(n=1)**	Positive (n=1)	• Decreased risk of spectacles use.

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Current Opinion in
Environmental Science & Health

Greenspace and health, wellbeing, physical activity, and development in children and adolescents: An overview of the systematic reviews

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Abstract

The evidence on the beneficial association of greenspace exposure and mental and physical health and wellbeing of children and adolescents is accumulating. We systematically searched PubMed, Scopus, and Web of Science for systematic reviews and/or meta-analyses on health, developmental, and behavioral outcomes in children and adolescents related to greenspace exposure, published until August 2022. Most of the available reviews are on mental health and behavioral outcomes. The evidence is mainly cross-sectional and conducted in high-income countries. Exposure assessment has been reported as the main methodological challenge in pooling the studies together. Outcome assessment and population characteristics are also among the reported sources of heterogeneity. Overall, reviews are suggestive of a beneficial association of greenspace with a range of outcomes (*e.g.*, birth, neurodevelopmental, cognitive, behavioral, weight-related, mental health and wellbeing, school performance, and physical and outdoor activities), except for allergic and respiratory outcomes for which the evidence is not conclusive.

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Keywords

Nature, Natural environment, Parks, Developmental outcome, Early life, Green space.

Introduction

The ongoing urbanization has led to an increase in the number of children being born and raised in urban areas [1]. Urban living is often associated with a stressful and sedentary lifestyle, increased exposure to urban-related environmental hazards such as air pollution, noise, and heat, and limited access or exposure to natural environments, especially greenspace [2,3]. Exposure to greenspace has been suggested to improve mental and physical health, wellbeing, and development in children and adolescents [4–6]. The ability of greenspace to exert such benefits has been suggested to be through socio-behavioral factors (*e.g.*, increase in physical activity, social cohesion, and attention restoration and a decrease in stress) [7] and environmental pathways (*e.g.*, mitigating the exposure to urban-related environmental hazards such as air pollution, noise, and heat and enriching microbiota diversity) [8,9]. Evidence that children and adolescents spend less time in nature than previous generations [10] has prompted researchers to explore the connection between exposure to greenspace and health in these age groups [11]. As a result, an increasing number of studies have evaluated this association [4]. Several systematic reviews up to now have summarized the greenspace-health studies in children and adolescents. Most of the reviews highlighted the inconsistencies in the findings to different extents according to the outcomes of interest. The observed inconsistencies might arise from exposure and outcome assessment, study design, and statistical issues [12]. Yet, the findings of the reviews on the associations and inconsistencies are not synthesized and remained fragmented. We aimed to systematically review the existing synthesized evidence (*i.e.*, systematic reviews and/or meta-analyses) on the association between exposure to greenspace and health, well-being, health-related

behaviors (*i.e.*, physical activity), and development in children and adolescents to summarize the current evidence and explore the knowledge gap.

Method

We adhered to the protocol for systematic search, article selection, evaluation, and synthesis according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement [25]. We searched PubMed, Scopus, and Web of Science on August 15, 2022, for systematic reviews and/or meta-analyses that reported an association between at least one of the measures of greenspace availability, accessibility, use, or quality and at least one health, wellbeing, behavioral, or development outcome in children (up to 18 years old) and adolescents (10–19 years old) (Tables S1–S4 present study population, exposure, comparison, outcome, and type [PECOS] criteria eligibility for the review, and the search queries used for databases). Considering the importance of temporality between greenspace exposure and outcome, we also included exposure during the prenatal period in this review. Narrative reviews and expert opinions were excluded as the selection of articles, quality assessment, and risk of bias assessment usually are not done for these types of evidence. In addition to the database search, we also conducted a manual search on the references lists of retrieved articles to identify additional studies. The studies underwent title, abstract, and full-text evaluation for the assessment of the eligibility of inclusion in the review (Fig. S1).

After completion of the selection process, relevant data on study characteristics (design, location, time of the study), study population (number of included studies in the review, study designs), exposures (type of exposure, source of exposure data, exposure assessment method, exposure allocation method), outcomes, risk of bias and quality assessment (methods and scores), results (main findings, effect sizes in the case of meta-analysis), and discussed strength and limitations were extracted (Endnote software was used for screening, and reference management). We synthesized the extracted information based on the type of outcome.

Results

We found 36 systematic reviews on the association between greenspace exposure and children's and adolescent's health (Fig. S1 shows the study selection process, and Table 1 shows the general characteristics of the included reviews) [4, 12–46]. Most of the reviews were on mental health outcomes and among the retrieved reviews only eight of them were supplemented with meta-analysis (Figure 1) [13,17,20,26,30,31,39,44]. Most of the reviews were only on English evidence, and other languages were only included in a few of the reviews. The evidence quality in terms of risk of bias in most of the reviews has been reported as "fair to moderate".

Greenspace exposure

Different exposure metrics and approaches (*e.g.*, use of different greenness indicators, buffer sizes and types, locations, and time points of year) have been used across the studies. Objective and subjective approaches have been used to quantify indicators of availability, access, and use. However, the body of evidence on indicators of use and subjective perceptions is small. Heterogeneity in exposure assessment and definition has been reported as one of the most common obstacles in comparing and pooling the available evidence for meta-analysis. Until now most of the studies have used the Normalized Difference Vegetation Index (NDVI) as the greenness indicator regardless of the type of outcome. NDVI has several strengths such as ease of access at multiple time points for around four decades, which can make it easier to compare the findings across studies and different time frames. Still, NDVI is a relatively crude measure, especially when considering outcomes such as allergic responses, as it does not distinguish between types of vegetation and does not account for the quality of greenspaces. In general, there has been no defined and straightforward approach across the studies for the selection of appropriate exposure indices, approaches, and parameters for greenspace studies, and further efforts are needed to clarify the best approaches for the selection and reporting of exposure metrics across the studies based on the evaluated outcomes and hypothesized underlying mechanisms as well as the availability of data.

Outcomes

Birth outcomes

Gestational length

Five systematic reviews [26,20,29,31,39] (among them four meta-analyses [26,20,31,39]) synthesized the available evidence on greenspace exposure and gestational length (all on preterm birth, defined as delivery at <37 weeks). A meta-analysis found a 13% decrease (95% confidence interval [CI]: 0.80: 0.94) in the odds ratio (OR) of having preterm birth comparing mothers living in areas with high vs. low levels of greenspace [20]. In contrast, another meta-analysis found no significant associations between residential greenness and preterm birth [39]. Mitigation of environmental hazards, promoting physical activity, and reducing stress have been the proposed mechanisms for this beneficial association of greenspace.

Fetal growth

Six systematic reviews [13,20,26,29,31,39] (including five meta-analyses [13,20,26,31,39]) synthesized the association between greenspace exposure and different fetal growth outcomes including low birth weight (birth weight <2500g), small for gestational age (birth weight <10th percentile of the sex and gestational age), and head circumference. Five of the reviews consistently reported a positive association between exposure to

Table 1

Characteristics of the systematic reviews and/or meta-analyses on greenspace exposure and children and adolescents' health until August 2022.

First author (Year)	Study type	Country	Review time span	Number of included article	Overall reported quality	Type of included studies	Population	Outcome
Dzhambov et al. (2014)	SRMA	Bulgaria	- to 2014	8	Mostly of moderate quality	Observational	Newborn	Birth weight
Gascon et al. (2015)	SR	Spain	- to 2014	4	NR	Observational	3–10 years	Emotional and behavioral problems including ADHD
de Keijzer et al. (2016)	SR	Spain	- to 2016	6	Mostly of fair quality	Observational	7–18 years	School performance, cognitive development, attention capacity, ADHD and DHD symptoms severity
Lambert et al. (2017)	SRMA	Australia	- to 2017	11	Overally with high quality	Observational	Children (up to 18)	Asthma and allergic rhinitis (asthma, wheeze, allergic rhinitis, lung function)
McCormick et al. (2017)	SR	Not clear	2012 to 2017	12	NR	No limitation	Children (up to 18)	Mental well-being
Lambert et al. (2018)	SR	Australia	- to 2018	5	Most of studies scored >70%	Observational	Children (up to 19)	Atopic sensitization to any allergen
Tillmann et al. (2018)	SR	UK	1990–2017	35	Mostly fair to good quality	No limitation (observational, qualitative, experimental)	Children (up to 18)	Mental health (emotional well-being, ADD, ADHD, self-esteem,stress, resilience, depression and health-related quality of life)
Twohig-Bennett et al. (2018)	SRMA	UK	- to 2017	6[b]	Not clear	Observational or experimental	Not clear	Preterm birth, small of gestational age, gestational age
An et al. (2019)	SR	USA	- to 2018	20	Moderate (7 out of 14)	Observational or experimental	Children (up to age 17)	Physical activity, obesity
Browning et al. (2019)	SR	USA	- to 2018	13	Majority with fair quality	Observational or experimental	8–18 years	Academic performance (test scores, grades, college preparatory exams)
Hartley et al. (2019)	SR	USA	2017 to 2019	7	NR	Observational	Children (up to 18)	Asthma
Lambert et al. (2019)	SR	Canada	- to 2019	4	Medium to high	Observational	Children (up to 18)	Time spent in outdoor play
Minch et al. (2019)	SR	Germany	- to 2019	14	Nearly all of the studies (13 out of 14) with low quality	No limitation	Children (up to 18)	Mental health, cardiovascular and sleep
Mygind et al. (2019)	SR	Denmark	2004 to 2017	36	Low quality	Observational or experimental	Children (up to 18)	Mental health, self-esteem, self-efficacy, self-concept, resilience, problem solving, academic performance, cognitive performance, mood, physical health, body mass index, psychophysiological stress, physical activity, social health, relational indicators, skill indicators, behavioral indicators

(*continued on next page*)

Table 1. (*continued*)

First author (Year)	Study type	Country	Review time span	Number of included article	Overall reported quality	Type of included studies	Population	Outcome
Akaraci et al. (2020)	SRMA	Australia	- to 2018	27	Medium to high quality	No limitation	Newborn	Birth weight, small for gestational age, low birth weight and preterm birth
Alejandre et al. (2020)	SR	UK	2010 to 2018	16	Mostly moderate and good quality	Observational or experimental	Children (up to 18)	Physical activity, body mass index, waist to hip ratio, vegetable consumption experience, eating behaviors
Dankiw et al. (2020)	SR	Australia	- to 2019	16	Significant methodological concerns reported	Observational or experimental	2–12 years	Physical activity outcomes and cognitive development (play, learning, creativity), social and emotional outcomes
Islam et al. (2020)	SR	Australia	2010 to 2020	23	NR	Prospective	Not clear	Perinatal health, physical exercise, neurodevelopmental health and respiratory health
Jia et al. (2020)	SRMA	China	- to 2018	21	Score of 10 out of 13	Observational	Children (up to <18)	Weight-related behaviors (*e.g.*, physical activity, sedentary behaviors and dietary behaviors), body mass index, overweight and obesity, waist circumference, waist-to-hip ratio and body fat
Lee et al. (2020)	SRMA	South Korea	- to 2019	10	Not clear (weak in outcome domains)	Observational	Newborn	Birth weight, low birth weight, preterm birth
Oswald et al. (2020)	SR	Australia	- to 2019	58	NR	Observational or experimental	Children (up to 18)	Mental health, cognitive function, academic achievement
Putra et al. (2020)	SR	South Korea	- to 2019	15	Mostly of fair quality	Observational or experimental	Children (up to 18)	Pro-social behavior
Roberts et al. (2020)	SR	UK	1978 to 2018	14	Most of the studies were weak	Qualitative and quantitative	Children (up to 21)	Affect and functioning, self-esteem, resilience, social resources
Zhang et al. (2020)	SR	New Zealand	2000 to 2019	14	Score of 7 out of 11	Observational	Adolescents (10–19)	Mental health outcomes (mood, stress, anxiety, depression, happiness, pleasure, emotional health, psychological health, and mental health)
Bikomeye et al. (2021)	SR	USA	- to 2020	6	NR	Experimental and Quasi-experimental	Children (up to 18)	Physical activity, physical and verbal conflict rates, pro-social behavior, mental well-being, emotionally positive interactions, play specific behaviors including antisocial behaviors, and solitary play
Daniels et al. (2021)	SR	USA	2011 to 2019	18	NR[a]	Observational and experimental	Children (up to 18)	Body mass index
Davis et al. (2021)	SR	Canada	2000–2020	45	Moderate	Observational and experimental	Children (up to 12)	Mental health and development, school achievement

Fleckney et al. (2021)	SR	Australia	2005 to 2020	19	NR	Observational	Adolescents (10–19)	Maternal health outcomes including depression or depressive symptoms, anxiety and stress
Fyfe-Johnson et al. (2021)	SR	USA	-to 2021	140	Moderate to high	Observational and experimental	Children (up to 18)	Physical activity, cognitive, behavioral, mental health, asthma and allergy-related conditions
Hu et al. (2021)	SRMA	China	- to 2020	29	Moderate to good quality	Observational	Newborn	Preterm birth, small of gestation age, low birth weight, birth weight, birth length, head circumference
Pitt et al. (2021)	SCR	Canada	- to 2021	32	NR	Observational	Children (up to 18)	Adiposity, mental health, respiratory outcomes, injury, mortality, allergic responses, health related quality of life,
Luque-García et al. (2022)	SR	Spain	- to 2021	34	Most with high, or probably high risk of bias	Observational	Children (6–12)	Brain volume, attention, visual and working memory, Intelligence, cognitive development, academic performance, self-discipline, mental health outcomes, well-being, ADHD symptoms, behavior
Sprague et al. (2022)	SR	USA	- to 2020	28	For most of outcomes it was moderate. For Allergy and weight related outcomes it was low.	Observational; Experimental; Quasi-experimental	Children (2–18)	Cognitive and brain development, mental health and wellbeing, attention and behavior, allergy and respiratory, and obesity and weight
Vella-Brodrick et al. (2022)	SR	Australia	- to 2021	12	Mostly of strong quality (83%)	Experimental and Quasi-experimental	Children (5–18)	Enhanced cognitive functioning
Ye et al. (2022)	SRMA	Australia	- to 2022	140	None of them had low quality	Observational	Children (up to 18)	Mental health, nutritional status, allergic and respiratory, circulatory health, general health, other.
Zare Sakhvidi et al. (2022)	SR	Iran	- to 2021	29	Fair	Observational	Children (up to 18)	Children behavior (total behavioral difficulties, ADHD symptoms and severity, ADHD diagnosis, conduct problems, pro-social behavior, emotional symptoms,peer-relationship problems, externalizing disorders, internalizing disorders)

SR: systematic review; SRMA: systematic review and meta-analysis; ADHD: Attention deficit hyperactivity disorder.

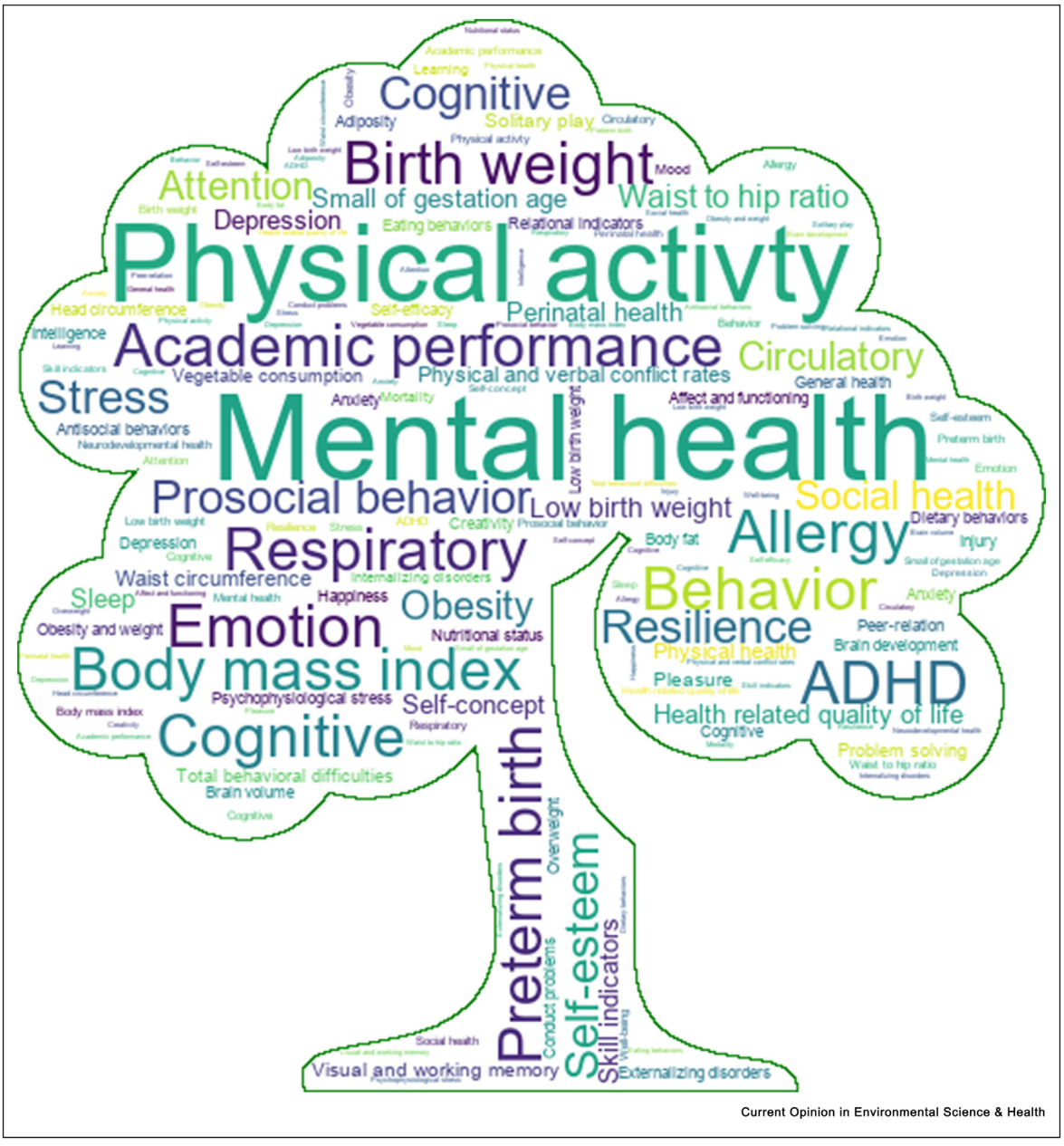
"-" in the "review time-span" column stands for from inception.

NR in the "overall reported quality" stands for not reported.

[a] All scored high according to the selected quality check list. And the authors concluded that their check list was not sensitive enough to detect low qualities.

[b] Review is on all age range. And the number of studies extracted from the children outcome with most retrieved studies (preterm birth).

Figure 1



Words cloud representation of the reported outcomes in the systematic reviews.

higher levels of greenspace and birth weight. Additionally, three of the reviews reported a negative association between greenspace exposure and the risk of low birth weight, but only one of them found significant associations [39]. The findings on small for gestational age were also suggestive of a beneficial role of greenspace [20,26,29,39]. One of the meta-analyses reported significant beneficial associations (pooled OR: 0.95; 95% CI: 0.92:0.97 for 0.1 unit increase in NDVI at 250−300m buffer size) [26]. Similar findings have been reported in another meta-analysis (pooled OR: 0.81; 95% CI: 0.76: 0.86 when compared highest with lowest exposure category); however, such a significant association was not observed on continuous outcome scales (pooled mean difference: -0.01: 95% CI: −0.05: 0.05 when compared highest exposure category with lowest exposure category) [20]. Dichotomizing the continuous variables could lead to false positive results, reducing power, concealing possible non-linearity, and uneven distribution of variables in each group. These could be a

possible explanation for the inconsistency between the continuous and dichotomous findings. Among the proposed mechanisms for beneficial associations, the most reported was stress reduction. Prenatal stress is a predictor of increased risks of low birth weight and preterm births. However, the role of mediating factors such as maternal physical activity and reduced exposure to air pollution should not be neglected. Pregnant women with higher deprivation (*e.g.*, lower education) were also suggested to benefit more from greenspace, probably because they have more free time and have increased opportunities to benefit from greenspace [47]. Therefore, socioeconomic factors could be responsible for reported heterogeneity across the reviews [39].

Neurodevelopmental outcomes

Fifteen systematic reviews (including one meta-analysis [44]) reported an association between greenspace exposure and different neurodevelopmental outcomes [11,14,15,25,28,29,32,34,36,38,41–45]. Here, we presented the available evidence in two broad groups of cognitive and behavioral outcomes.

Cognitive outcomes

Different cognitive neurodevelopmental outcomes such as cognitive performance and language, motor, and social abilities have been reviewed in 11 systematic reviews [15,25,28,29,32,36,38,41–44]. The reviews consistently reported a positive association between greenspace exposure and cognitive development in children. A review on cognitive and brain development found a significant positive association in half of the studies for working memory, cognitive performance, and white and gray matter volume in different regions of the brain [42]. However, the percentage of positive or significant findings across the reviews was different according to the review characteristics such as the year of conduction of the review, and the number and type of the included studies.

Behavioral outcomes

We found 11 reviews that reported results of behavioral outcomes [11,12,14,25,28,29,34,38,41,42,45]. Reported outcomes were mainly problematic behaviors (emotional symptoms, conduct problems, hyperactivity/inattention, peer relation problems, and attention deficit-hyperactivity disorder (ADHD)), pro-social behavior, self-determination, and self-regulation. A review of eight studies found a beneficial role of greenspace on behavioral outcomes in most of the included studies (seven out of eight) [42]. Another review on pro-social behaviors in children and adolescents found that about 70% of the reported associations were beneficial, of which around 30% were statistically significant [12]. The findings were reported to be similar, regardless of the socioeconomic status of children [29,34]. However, the findings on some of the outcomes were heterogeneous. For example, a review of children's behaviors found no supportive evidence for a beneficial association of greenspace on conduct problems in children [45]. Different mechanisms have been proposed for the neurodevelopmental benefits of greenspace including stress reduction, cognitive restoration, higher levels of physical activity, enhanced social interactions, and decreased exposure to air and noise pollution [43]. Available reviews highlighted the need for more studies in the low- and middle-income countries (LMICs) as most of the evidence is coming from high-income Northern American and western European countries, which could limit the generalizability of the results [42]. Also, there is a need for future mechanistic studies to explore possible pathways [41]. The available studies on neuroanatomical and neuroimaging outcomes such as brain anatomy and function are very limited and need further studies to replicate the previous findings on different populations, types, and quality of greenspace, and other neuro-cognitive outcomes. Additionally, whether greenspace exposure could lead to structural change and development of the brain needs to be further developed in the future.

Mental health and wellbeing

Mental health-related outcomes are reported in 14 systematic reviews [4,19,24,25,32–34,36–38,40–42,44] (including one meta-analysis [44]). A recent review found that more than 40% of original studies on greenspace and children's health were on mental health-related outcomes [44]. The reported outcomes were depression, anxiety, psychological distress, and psychological wellbeing. Most of the evidence (around 70%) are coming from cross-sectional studies [38], and only 30% of them were from cohort studies [44]. In general, most of the studies found a protective association for at least one mental health outcome (around 80%) [38]. A review of immersive nature experiences found nearly 60% of the included studies in the review reported an improvement in mental health outcomes following immersive nature experiences [25]. The number of experimental and randomized clinical trials in this area is still limited. However, a review found all the available randomized controlled trials reported a positive effect of greenspace on mental health outcomes in children [38]. The availability of studies with adverse effects (*e.g.*, anxiety and violence) has also been reported in a few reviews [44]. The proposed mechanisms for a protective role of greenspace on mental health-related outcomes in children focused on three pathways including environmental pollution mitigation (reducing harms from environmental hazards such as air pollution, traffic noise, and extreme heat), facilitating physical activities and social interactions, and inducing restorative experiences and stress reduction. Other mechanisms such as a buildup of microbiome diversity have been proposed to describe the positive influence of greenspace on children's mental health.

School performance

Nine systematic reviews [4,15,19,22,25,32,36,41,44] (including one meta-analysis [44]) reported an association between greenspace exposure and academic performance. In general, the literature on greenspace and academic performance is small, showing mixed findings, and most are based on observational, school-level study designs. A review of the 13 studies, found that around one-third of the reported associations were significantly beneficial, whereas less than 10 percent were significant and detrimental. Most of the evidence (around 60%) was non-significant [22]. It seems that greenspace is not effective same for all the school achievement outcomes. For example, Browning and Rigolon [22] found that end-of-semester grades and college preparatory exams showed greater shares of positive associations for math or reading test scores, whereas most findings regarding writing test scores were non-significant. The hypothesis behind the possible association between greenspace exposure and school achievements is that it can foster performance and help reduce stress and distractions. Different mechanisms including attention restoration, better mental health, more outdoor time, more physical activity, and better physical health have been proposed for these beneficial associations. Several confounding and moderating factors may affect the relationships including parental characteristics, school and environmental factors, socioeconomic status, gender, and urbanization. Additionally, a considerable share of the studies on school performance had an ecological design that can be affected by the ecologic fallacy problem.

Physical activity and time spent outdoor

Nine systematic reviews [16,21,25,27,28,29,30,34,38] (including one meta-analysis [30]) reviewed the available studies for the association between greenspace and physical activity in children and adolescents. Across the reviewed studies, physical activity has been measured and reported in different methods such as percentage of time spent in moderate to vigorous physical activity (MVPA), time spent in sedentary and light physical activity, percentages or the number of children observed in different activities in green spaces, physical activity frequency and distance, and use of a pedometer and accelerometer data. Available reviews found a positive association between greenspace (residential or schoolyard [34]) and physical activity or time spent outdoor [16,25,27,30,34,38]. However, the reviews reported few sporadic studies that reported a negative or null association between greenspace and physical activity or time spent outdoor [30,48–50]. In a review of seven studies on the effect of nature play intervention on physical activity three of the studies found no significant role of nature play intervention/exposure relative to traditional play settings [28]. One review concluded stronger benefits for boys and the associations were also stronger with an increase in age [29]. The beneficial influence of greenspace on children's physical activity could be associated with quality characteristics of green spaces (*e.g.*, density, foliage, proximity), activity type (*e.g.*, formal vs. informal plays and activities), demographic characteristics of children (*e.g.*, sex, ethnicity, and parent-children relationship) [27].

Weight-related outcomes

Different weight-related measures including body mass index (BMI), waist-to-hip ratio, BMI trajectory, skinfold thickness, body fat, overweight/obesity, and insulin resistance have been used across eight systematic reviews [21,25,27,30,35,40,42,44] (among them two meta-analyses [30,44]). The reported associations were mixed, but most of the reviews concluded a potential beneficial role of greenspace at least on one of the aforementioned attributes. A recent meta-analysis of five studies investigating the association of residential surrounding greenness (measured by NDVI) with obesity/overweight found lower odds of obesity/overweight in children (OR: 0.91, 95%CI: 0.84 to 0.98 per 0.1 unit increase in NDVI) [44]. A review of immersive nature experience studies found BMI decreased after a 16-week adventure therapy program; however, the risk of bias in the studies was high due to not including control [25]. In addition to children's characteristics such as sex and socioeconomic status (SES), greenspace characteristics such as type (*e.g.*, park, forest) and location (*e.g.*, home, school) could be responsible for the variations in the observed associations [27].

Allergy and respiratory

Association between greenspace exposure and different allergy and respiratory outcomes (asthma, allergic rhinitis, respiratory sinus arrhythmia, allergic rhinitis, eczema, atopic sensitization, wheezing, pneumonia, bronchitis, lung function, and other respiratory conditions) in children and adolescents has been reported in six reviews [17,18,23,42,44,29]. Current evidence on the association of greenspace exposure with allergic and respiratory health and diseases is inconsistent, both in terms of direction and strength [44]. Two meta-analyses found no significant association between greenspace and asthma [17,44]. A review concluded that certain plant species increase asthmatic symptoms indicating that the type of plant is an important determinant in the heterogeneity of the findings [29]. The evidence on lung function is very limited (five studies reported in one review), and in general, are suggestive of the beneficial role of greenspace exposure for lung function in children and adolescents. The protective studies postulated the mitigating role of greenspace on the environmental pollutants and enhancing physical activity, and more diverse microbial exposure as the mechanisms for a potential protective role of greenspace on allergy and respiratory outcomes [44]. On the other hand, increasing pollen exposure is proposed as a mechanism for the observed detrimental associations.

Cardiovascular and circulatory outcomes

Two studies reviewed the evidence on the association between greenspace exposure and different cardiocirculatory outcomes such as systolic and diastolic blood pressure, arterial pressure, risk of hypertension, blood lipids profile, combined cardiometabolic score, allostatic-based index, retinal vessel diameter, and heart rate variability in children [24,44,]. Most of the evidence (80%) was from the cross-sectional studies [44], and blood pressure is the most commonly reported outcome. Most of the findings for blood pressure outcomes were suggestive of the beneficial (inverse) association of greenspace exposure with blood pressure in children and adolescents. The positive role of greenspace on children and adolescent health can be postulated through the mitigation of cardiovascular risk factors such as air and noise pollution, stress reduction, and increasing physical activity.

Discussion

Most of the reviews generally reported a beneficial role of greenspace on children's and adolescent's health. However, for a part of the outcomes (*e.g.*, allergy, respiratory outcomes, or conduct problems), the available evidence is not conclusive. Different mechanisms such as reducing stress, mitigation of urban-related environmental hazards, increasing physical activity, social interactions, microbial diversity, and cognitive restoration could be expected for the observed beneficial associations. Considering the role of mediators and modifiers is important in the interpretation of the findings and also draw a conclusion about the possible mechanism(s). Available reviews have mainly overlooked these issues and therefore these topics could be considered as open questions in future reviews. Included reviews attributed the observed heterogeneity mainly to exposure assessment and claimed that the diverse findings across the studies are probably due to the use of inappropriate greenspace indices. Part of the heterogeneity could be due to the different susceptibility of the population to the effects of greenspace (*e.g.*, different socioeconomic status). Mediation and modification of the associations by different factors (*e.g.*, mediation by physical activity, or modification by personal traits) are among the topics that have not been considered systematically in the available reviews. Outcome assessment was also claimed as another important source of heterogeneity that should be considered in future studies. For example, for mental health, weight status, and asthma and allergic outcomes, reliance on guardian or teacher reports for kids' health indicators may have resulted in the misclassification of outcomes [17,44,]. Additionally, the diversity of the populations in terms of socioeconomic status, gender, age, personal preferences, and perception of nature was discussed as the source of variation across the studies [13]. Several other methodological issues such as considering the role of possible mediators, and the window of susceptibility (especially for birth outcomes) are among the highlighted shortcoming of available studies and should be considered in future research [13]. In conclusion, the body of evidence on the association between greenspace exposure and children's health is diverse in terms of direction and magnitude, mostly inclined towards a beneficial role of greenspace for children and adolescents' health, wellbeing, and development. The evidence is stronger on mental health and behavioral outcomes, and the studies on outcomes such as respiratory, circulatory and brain functions are limited, and highlight the needs for further research. Future longitudinal studies, especially in LMICs, are needed that include different measures of greenspace exposure (*e.g.*, use of green space, visual access to greenspace, and indoor plants in addition to surrounding greenspace and access to green spaces) and repeated characterization of outcomes and relevant covariates/confounders and modifiers, which also shed light on potential mechanisms underlying such associations. The association of the greenspace exposure with improved health, well-being, development, and behaviors could differ in terms of its relevance and the underlying mechanisms in different age groups (developmental, childhood, etc.). Therefore, future reviews need to do evidence synthesis based on the age groups of participants. Additionally, systematic reviews on the health effects of greenspace on children and adolescents are highly suggested to compare and provide recommendations based on different type of greenspace, greenspace exposure measures, and exposure assessment methods.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

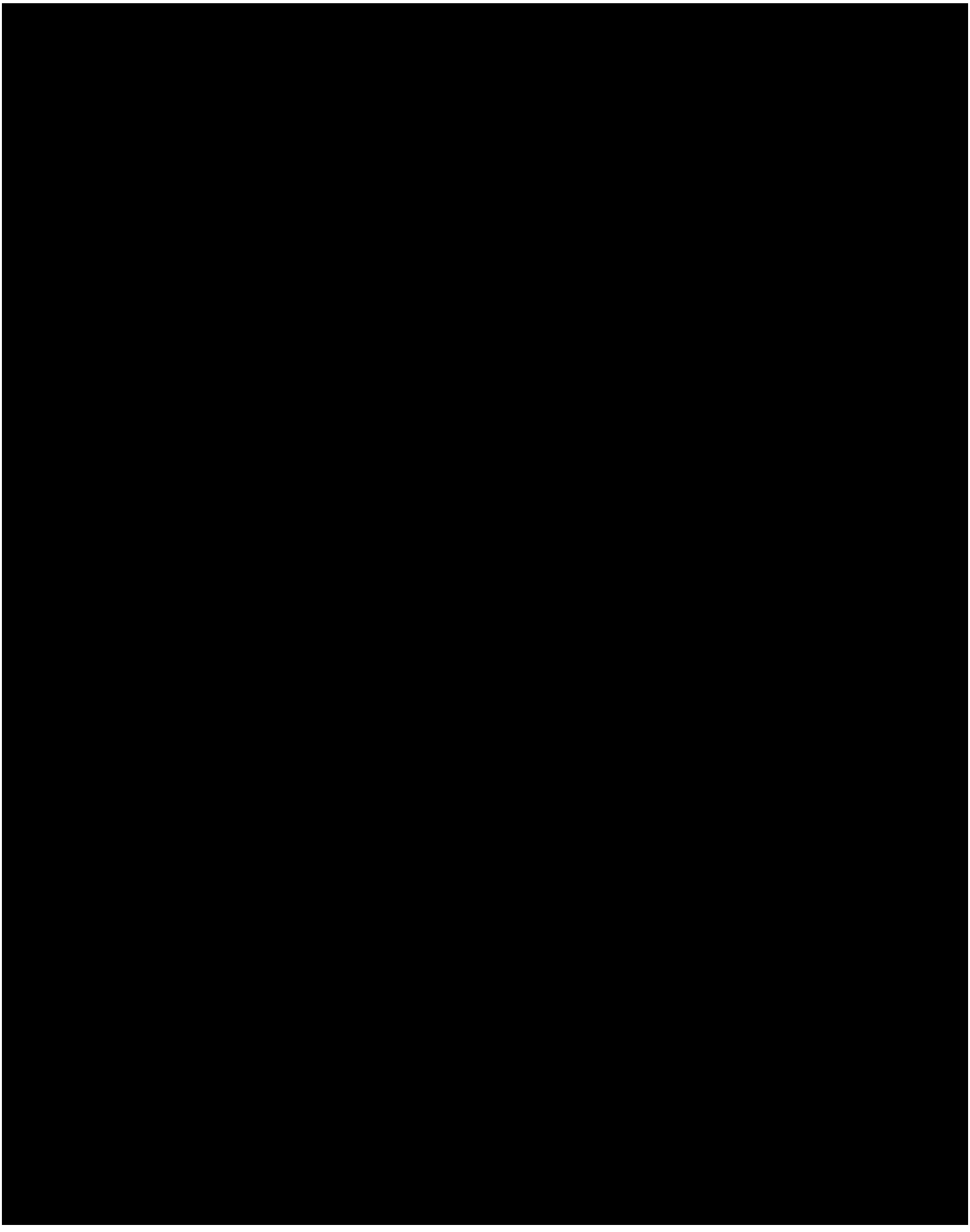
Supplementary data to this article can be found online at https://doi.org/10.1016/j.coesh.2023.100445.

References

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest
** of outstanding interest

1. [redacted]





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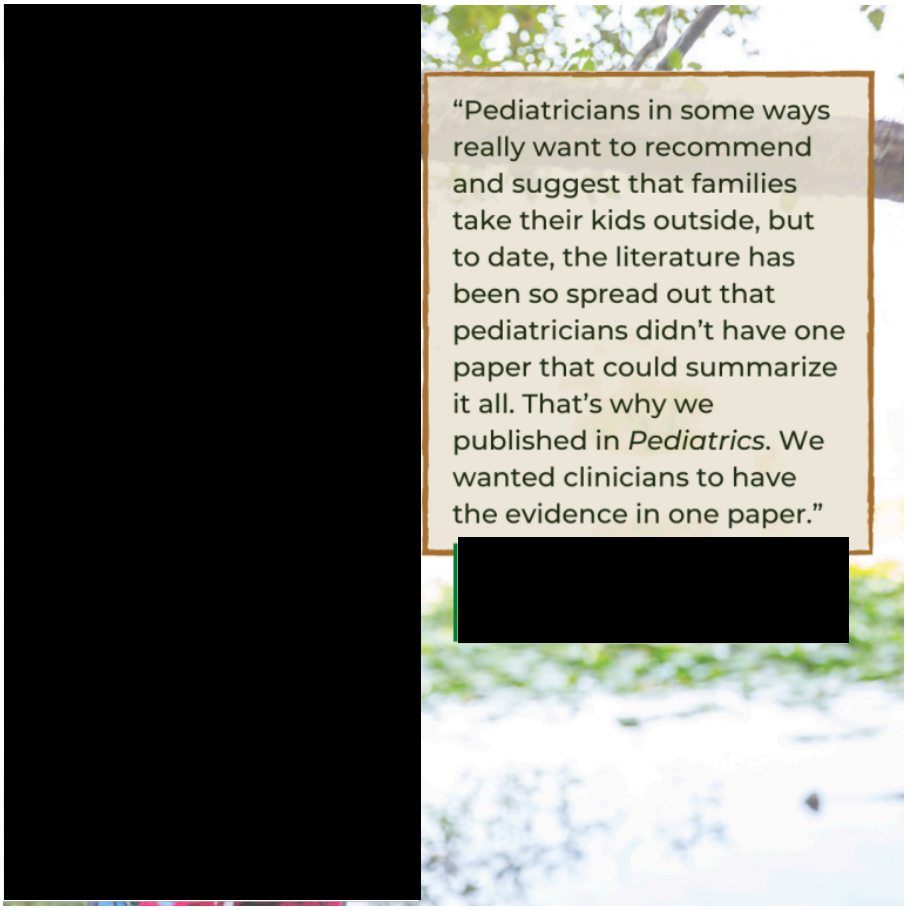
Nature and Children's Health: A Systematic Review

Citation

[redacted]

LINK TO FILE (HTTPS://PUBLICATIONS.AAP.ORG/PEDIATRICS/ARTICLE-ABSTRACT/148/4/E2020049155/181269/NATURE-AND-CHILDREN-S-HEALTH-A-SYSTEMATIC-REVIEW?REDIRECTEDFROM=FULLTEXT)

Abstract



(https://publications.aap.org/pediatrics/article-abstract/148/4/e2020049155/181269/Nature-and-Children-s-Health-A-Systematic-Review?redirectedFrom=fulltext)The American Academy of Pediatrics has long recognized the importance of play and has encouraged outdoor play to promote children’s health and social-emotional development. Outdoor play environments vary widely, from urban parking lots to grass sports fields to wilderness. There is increasing evidence that outdoor play environments containing natural elements may offer health benefits that come specifically from engaging in the natural world. Recent studies have demonstrated that a broad range of outcomes are related to access to, and contact with nature, including increased physical activity, reduced obesity, decreased stress, and improved mental health.

However, nature contact is not regularly experienced by all children because of urbanization, sedentary indoor lifestyles, and disparities in access to green space. Neighborhoods with more socioeconomically disadvantaged residents and families of color tend to have fewer nearby residential parks, and financial and transportation limitations that prevent access to parks and wilderness outside of city limits. This inequity extends to school grounds in low-income neighborhoods, which are less likely to have school gardens compared with schools in high-income neighborhoods. Furthermore, there is evidence that contact with nature and green space may disproportionately benefit disadvantaged populations by attenuating the toxic effects of poverty: the so-called “equigenic” effect. For these reasons, promoting nature contact and ensuring equitable access to green spaces could play a role in improving health outcomes and behaviors, and reducing health disparities.

Pediatricians are uniquely positioned to offer guidance about evidence-informed interventions to promote child health during clinical interactions, and through community advocacy. Our goal was to conduct a systematic review to aggregate and evaluate the evidence regarding the effects of nature contact on children’s health, and to make it available to pediatric health care providers.

Therefore, we explore the full breadth of quantitative evidence with a systematic literature search and consensus-based review process to make the evidence accessible on which to base clinical recommendations, health-promoting programs, and policies and to guide future research.

Related News

- As Outdoor Preschools Gain Traction, States Work to Unlock Funding (https://www.the74million.org/article/as-outdoor-preschools-gain-traction-states-work-to-unlock-funding/) (January 27, 2023)
- Nature is Nurture: Outdoors are Key to Children's Health, Buffer to Pandemic Stress [redacted]) (November 5, 2021)
- Children with access to nature are mentally and physically healthier [redacted] (September 30, 2021)
- Science backs nature as key to children's health [redacted] (September 29, 2021)

OUR WORK

EVENTS

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SEP 22 //

Nature and Health Fall Community Dinner

[redacted])

[redacted]

Educational Psychology Review (2022) 34:1217–1254
https://doi.org/10.1007/s10648-022-09658-5

REVIEW ARTICLE

Effects of Nature (Greenspace) on Cognitive Functioning in School Children and Adolescents: a Systematic Review

[redacted]

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Abstract

There is growing interest in understanding the extent to which natural environments can influence learning particularly in school contexts. Nature has the potential to relieve cognitive overload, reduce stress and increase wellbeing—all factors that are conducive to learning. This paper provides a PRISMA-guided systematic review of the literature examining the effects of nature interventions on the cognitive functioning of young people aged 5 to 18 years. Examples of nature interventions include outdoor learning, green playgrounds, walks in nature, plants in classrooms and nature views from classroom windows. These can vary in duration and level of interaction (passive or active). Experimental and quasi-experimental studies with comparison groups that employed standardized cognitive measures were selected, yielding 12 studies from 11 papers. Included studies were rated as being of high (n = 10) or moderate quality (n = 2) and most involved short-term nature interventions. Results provide substantial support for cognitive benefits of nature interventions regarding selective attention, sustained attention and working memory. Underlying mechanisms for the benefits were also explored, including enhanced wellbeing, cognitive restoration and stress reduction—all likely to be contributors to the nature-cognition relationship. The cognitive effects of nature interventions were also examined according to age and school level with some differences evident. Findings from this systematic review show promise that providing young people with opportunities to connect with nature, particularly in educational settings, can be conducive to enhanced cognitive functioning. Schools are well placed to provide much needed 'green' educational settings and experiences to assist with relieving cognitive overload and stress and to optimize wellbeing and learning.

Keywords Cognitive functioning · Nature · Greenspace · Learning · Children · Adolescence

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Introduction

The pressure of modern-day westernized living involving technology, high-rise buildings, traffic congestion and pollution is taking a toll on society. These lifestyle changes have led to reduced opportunities for interacting with nature (Hartig et al., 2014) and a fast-paced lifestyle that can be psychologically draining. Subsequently health and well-being are compromised as evidenced by escalating rates of mental illness (Blake et al., 2018; Michaelson et al., 2020; Vancampfort et al., 2018). In an attempt to reduce fatigue and improve well-being, research attention has turned to the potential healing effects of nature (Capaldi et al, 2015; Diaz et al., 2015; Hartig et al., 2014).

Nature or natural environments are broadly defined as including living plants and animals, geological processes and weather. Nature exposure typically involves connecting with 'green' and 'blue' spaces including park land, forests, plants, the ocean and other natural waterways such as rivers and lakes. These can vary substantially in exposure time (from minutes to weeks and even years), as well as the extent to which nature is the core of the activity rather than simply in the background (Norwood et al., 2019). For example, nature interventions can include going for a walk amidst nature for 30 min, right through to creating a school garden which can last months or years. Multiple theories have been presented to explain the relationship between nature and different aspects of health. The Biophilia hypothesis (Urlich, 1983) posits that individuals are innately driven to affiliate with nature for survival and psychological restoration. When a connection with nature occurs, there is an opportunity for cognitive capacities to be relieved and well-being to be strengthened. The Attention Restoration Theory (ART; Kaplan, 1995) asserts that elements of the natural environment elicit a soft fascination from individuals that can release the need for relentless goal-directed attentional processes often associated with immersion in built environments and subsequently provides cognitive restoration. The Stress Reduction Theory (Ulrich, 1983; Ulrich et al., 1991) focuses on physiological responses to demonstrate that a reduction in stress induced by the natural environment can, in turn, enhance cognition. These theoretical perspectives offer a common theme of restoration through enhancing well-being by reducing mental fatigue or stress and are consistent with Wilson's concept of 'biophilia' (1984). This suggests that exposure to nature can be helpful in learning environments where cognitive functioning is fundamental. It is the broad aim of this paper to undertake a systematic review of high-quality studies examining the effects of nature (greenspace) on the cognitive functioning of school children and adolescents. This will include a broad range of passive and active nature interventions, of varying duration, that are common in school settings. This will provide insights into whether specific theoretical perspectives are most relevant for particular types of interventions (e.g., short term or active).

There has been a keen interest in exploring the extent to which children and young people connect with nature, value nature and benefit from nature (e.g., Barrable & Booth, 2020; Roberts et al. (2020). This in part stems from concern about

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the rising rate of children growing up in urban environments and missing out on time spent outdoors in the natural environment (Weeland et al., 2019). Children have been identified as a population group with specific risks and needs relating to attention, self-regulation as well as physical and cognitive development (Roberts et al., 2020). The role of nature in assisting young people with these issues has preliminary empirical support, albeit with more diverse samples (Hartig et al, 2014) such as with older adults for memory enhancement (Astell-Burt & Feng, 2020). This has prompted interest in understanding how nature exposure can influence children's cognitive development and learning particularly in school environments. For example, consistent with ART, it is plausible that exposure to nature can help children to replenish depleted cognitive resources resulting from information overload. An attraction to nature can trigger 'soft' (effortless) fascination, relieve fatigue and aid psychological replenishing. In support of this, van den Berg et al. (2016) found that university students and staff who viewed 40 images of natural and built scenes and rated these on complexity and restorative quality (fascination, beauty, relaxation and positive affect) recorded longer viewing times for the nature scenes—consistent with greater fascination with nature—and rated them as more restorative than built scenes.

Most of the empirical studies on nature are correlational designs. For example, Flouri (2019) examined the relationship between neighborhood greenspace and spatial working memory for 4,758 children aged 11 years living in urban areas of England. They found that less neighborhood greenspace (measured by satellite imagery) was related to poorer spatial working memory for these children. A study by Li et al., (2019) examined the relationship between tree cover density proximal to schools and academic performance for 624 high school students. They found that tree cover density in school surroundings was positively associated with academic performance (measured using Illinois Report Cards, American College Test scores and graduation rates). A study including 101 public high schools in Michigan examined whether nature exposure—nature views from school buildings, vegetation levels on campus and the potential for students to access this vegetation—was positively related to academic performance (e.g., Educational Assessment Program test and graduation rates) and inversely related to antisocial behaviors (Matsuoka, 2010). They found that landscapes of mowed grass and parking lots were associated with poorer student performance, whereas landscapes composed primarily of trees and shrubs were correlated with favorable academic performance. With few exceptions (e.g., Markevych et al., 2019), the majority of studies have found a positive relationship between nature exposure and cognitive functioning for children. In addition, learning in greenspace or viewing nature from a classroom has also been associated with reduced heart rate and cortisol levels (Dettweiler et al., 2017; Li & Sullivan, 2016). These favorable findings also extend to longitudinal studies whereby greater exposure to residential surrounding greenspace over one's life, particularly in childhood, was associated with enhanced cognitive functioning and brain density (e.g., Dadvand et al., 2015).

A limitation of correlational studies is that causal relationships cannot be established, nor do they enable a clear understanding of the factors that influence the beneficial effects of nature on cognitive functioning. Kuo et al. (2019) examined some

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of these influential factors for enhancing cognitive functioning in learning environments and identified improved self-discipline, heightened motivation, enjoyment and engagement, as well as increased physical activity and fitness. They also noted some indirect effects of nature on learners such as the calm, quiet and safe contexts often associated with nature, which then facilitate warmer and cooperative social interactions and self-directed creative play. They also proposed the notion of a synergistic effect of the numerous processes underlying the nature-learning connection. For example, nature can simultaneously increase concentration, engagement and self-discipline to enhance learning. Although Kuo et al., (2019) provide (limited) empirical support for each of these processes, they note concerns relating to the poor-quality studies and over-generalization of results in this field.

The interest of this systematic review lies in the population of school children and since this group spans a long time period, it is important to examine how nature affects children at all stages of their development. Neighborhood greenness can play an important role in cognitive development starting from the very early stages of life (Dadvand et al., 2018; Liao et al., 2019) and continuing through to later stages of childhood (Flouri, et al., 2019; Lee, et al., 2019). Dadvand et al. (2018) reported long-term exposure to greenness early in child development to be associated with beneficial structural changes in the brain. Liao et al. (2019) observed that exposure to neighborhood greenspace is associated with better early childhood neurodevelopment for those up to 2 years of age including prenatals. Mason et.al. (2021) examined the impact of short-term (from 10 to 90 min) passive nature exposure on cognitive functioning in primary, secondary and tertiary students. They found that 12 out of 14 studies reported restorative effects of greenspace for attention and working memory for all education sectors. The authors suggest that different mechanisms may be involved in long-term nature exposures, and hence, this distinction warrants further investigation.

Some researchers have examined age differences in the relationship between greenspace and cognitive functioning. For example, Lee, et al., (2019) included 6–18 year old children in their study and found that both the younger and older groups showed inverse relationship with greenness and attention problems, indicating that nature may benefit children throughout their development. In a longitudinal study, Reuben et al. (2019) observed associations between greenspace exposure and cognitive performance across all ages. Children were assessed on fluid and crystalized intellectual performance at ages 5, 12 and 18. After adjusting for socioeconomic status, greenspace exposure predicted longitudinal benefits for fluid cognitive ability among 5 year-old children. These findings add to the body of research on the importance of nature in early brain development.

Experimental studies with children are emerging but these generally have weak study designs, include short-term nature exposure, or focus on specific samples. For example, a within sample study comprised 17 students aged 7–12 years diagnosed with ADHD (Faber et al., 2009). Each student completed three walks, one week apart (and in random order). One walk was in a city park and the other two walks in well-kept urban locations (downtown and neighborhood). Performance on a Digit Span Backward task was found to be better after the park walk relative to the urban walks. These results are promising, but the extent to which these findings apply to general student populations

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is unknown. More recently, reviews and meta-analyses on the effects of nature on desirable psychological and health outcomes have been published and include mostly randomized controlled trials with general samples (Stevenson, et al., 2018), including those with samples of children and adolescents (Mygind et al., 2019; Roberts et al., 2020). For example, a systematic review by Vanaken and Danckaerts (2018) included 21 studies examining the impact of greenspace on children and adolescents' mental health. They concluded that the evidence is consistent in demonstrating the favorable influence of exposure to greenspace on emotional and behavioral issues such as inattention and hyperactivity. A mini review of nature connection interventions for children was also published with the aim of identifying themes and trends (Barrable & Booth, 2020). The authors also noted poor study quality and they proposed guidelines for future work to strengthen the quality of evidence collected by researchers.

Some age differences in level of nature connection have been reported between younger children (10–12 years) compared with adolescents (13–15 years), with younger age groups reporting higher levels (Braun & Dierkes, 2017). However, no firm conclusions can be drawn as work examining nature exposure and cognitive outcomes with children is scarce. More research is needed to collate the findings from well-designed experimental studies to better understand the effects of nature on children and adolescents' cognitive capacity in school settings and their underlying mechanisms.

The main purpose of this review is to examine evidence of a causal relationship of nature exposure on cognitive functioning for the population of school children and adolescents in a variety of settings. Specifically, we review studies of diverse time exposures, from a few minutes to months and years, to capture any short-term benefits for attentional processes, as well as those for longer-term benefits like academic performance. Therefore, our definition of nature exposure was intentionally broad and could include activities where nature plays a background role, like passive viewing of the natural environment while sitting in a classroom or walking in a park or it might include activities where nature plays an active role like in outdoor gardening lessons.

More specifically this review will: (1) systematically evaluate the recent body of experimental and quasi-experimental studies examining the effects of nature (greenspace) on cognitive functioning in children and adolescents; (2) investigate the underlying processes involved in possible effects of nature on cognitive performance as well as consider the adequacy of different theoretical models to explain any effects; and (3) examine whether the effects of nature exposure differ according to age. We will also explore the duration and type of nature intervention (active or passive) to determine whether these intervention characteristics influence outcomes.

Method

Literature Search and Eligibility Criteria

An a priori protocol was designed and registered with PROSPERO (registration number: CRD42021214826). The checklist of the Preferred Reporting Items for

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Systematic Reviews and Meta-Analyses (PRISMA) was applied to guide the systematic review process and began with the PICOS process to develop our main research question and to determine appropriate search terms. A PICOS structured question was formulated based on the population, intervention and outcome of interest and was: What are the effects of nature (greenspace) on cognitive functioning for school aged children and adolescents? Key components included nature exposure interventions examining cognitive outcomes, focus on school aged children, and the inclusion of high-quality studies employing experimental and quasi experimental research designs. For each component, relevant search terms were identified and then converted to keywords (see Table 1). The various search queries were based on a combination of keywords.

Three types of keywords targeted papers on nature or greenspace environment combined with cognitive outcomes, and school children population. An example of a search for the Effect of Nature on Cognitive Processes in School Children in Scopus is: ((TITLE-ABS-KEY (“school environment” OR child* OR “school landscape*” OR childhood OR pupil* OR "high-school student*")) AND (TITLE-ABS-KEY (“green break” OR “green area” OR “view* of nature” OR “nature exposure” OR “nature walk” OR “exposure* to nature” OR outdoor* OR greening OR greenspace OR greenness))) AND (TITLE-ABS-KEY (“restorative effect” OR “psychological recovery” OR “effect* on attention” OR “executive function*”OR “cognitive restoration” OR attention* OR cognitive OR "mental fatigue")).

Study selection criteria were: (a) the research study was written in English; (b) the study design was experimental or quasi experimental (e.g., participants or class of students randomly assigned to a group, pre- and post-assessments, comparison group or controlled trials); (c) exposure to nature included parks, school playgrounds, neighborhood green areas, nature views from the window or inclusion of plants inside a room; (d) nature exposure was based on expert assessment or described in detail and/or a picture was provided and/or validated questionnaire methods; (e) the study reported a measure of cognitive functioning using

Table 1 Development of research question and search strategy based on PICOS

PICOS	Concepts	Keywords/Inclusion Criteria
P (Participants)	School Children	school environment OR child* OR school landscape* OR childhood OR pupil*
I (Intervention)	Nature Exposure	green break OR green area OR view* of nature OR nature exposure OR nature walk OR exposure* to nature OR outdoor* OR greening OR greenspace
C (Comparison)	Urban, Classroom	urban walk, classroom
O (Outcome of interest)	Enhanced Cognitive Functioning	restorative effect OR psychological recovery OR effect on attention OR executive function* OR cognitive restoration OR attention OR cognitive
S (Study Design)	Comparison Group	experimental OR quasi-experimental OR RTC

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standardized instruments (academic records, cognitive performance tests); (f) the study focused on school children and adolescents between 5 to 18 years of age; (g) no restriction on publication date was given. Studies were excluded if they: (a) were descriptive, observational, or a case study with no pre-/post-treatment design; (b) did not include an objective description of greenspace, or, in case of a subjective description, if there was no standardized or expert assessment of greenspace; (c) focused on children during the prenatal period or pre-school children.

The initial database searches were conducted between March and May, 2020 and updated regularly with the final update in May 2021. They were run on ELSEVIER and EBSCOhost engines through the following databases: Scopus, PubMed, Academic Search Complete, CINAHL Complete, Education Research Complete, ERIC, SocINDEX with Full Text and Urban Studies Abstracts. A total of 1393 journal papers were found, as presented in Fig. 1. In addition to the database searches, an

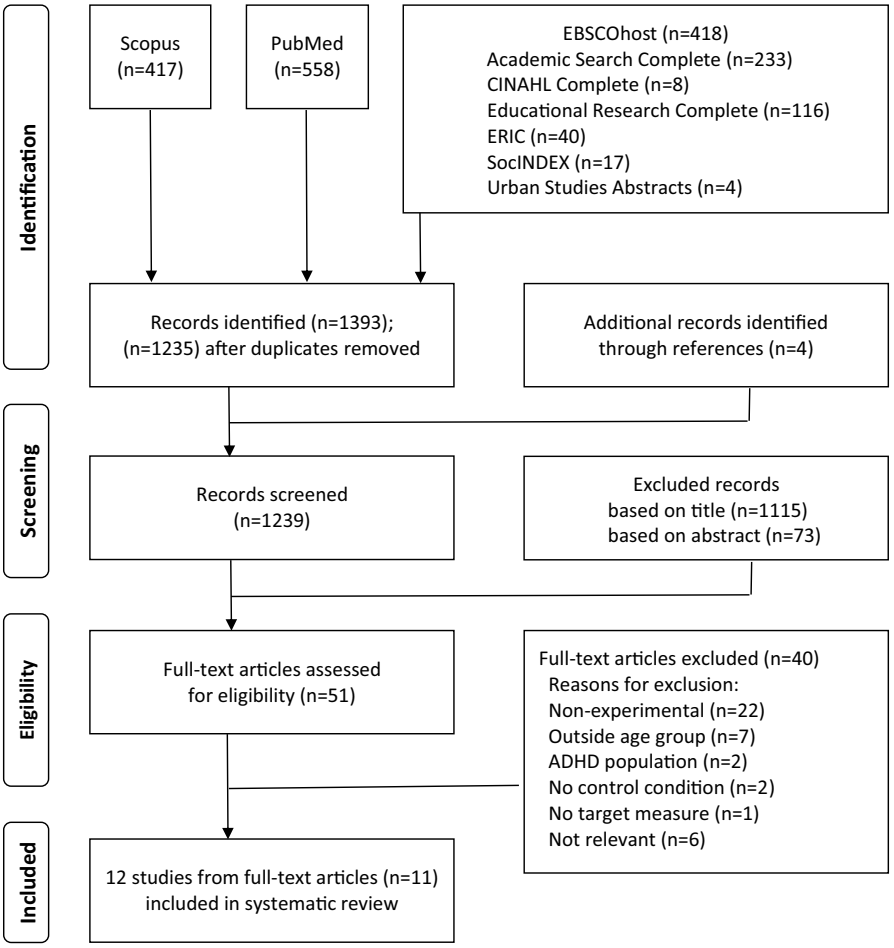


Fig. 1 PRISMA flow diagram

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ancestry search that checked reference lists of key papers, and a hand search of relevant journals and grey literature were also conducted to ensure all relevant works, including unpublished but publicly available works and dissertations were included in the review. Four additional studies were identified based on reference lists of key papers. All duplicates were removed, which reduced the results to 1235.

The screening process started with removing irrelevant papers. Articles were first excluded based on titles (n = 1115), and the remaining articles were screened based on abstracts. Subsequently, the title-abstract screening process resulted in 51 articles to go through to the next stage of full-article review. The full texts of the remaining studies were carefully evaluated by both authors according to the exclusion–inclusion criteria. Eleven papers comprising 12 studies were selected for the systematic review. Reasons for the exclusions are presented in the PRISMA flowchart (Fig. 1).

The following information was extracted from the selected studies: author, year of publication, country, research focus or question, theoretical model, sample, measures, study design, intervention/comparison group and findings. See Table 2.

Quality Appraisal of Studies

An appraisal of the quality of studies to be included in the review was based on the Effective Public Health Practice Project Quality Assessment Tool (EPHPP) for Quantitative Studies (2010). The EPHPP has been shown to have robust psychometric properties and is suitable for systematic reviews of effectiveness (Deeks et al., 2003; Jackson & Waters, 2005; Thomas et al., 2004). The EPHPP assesses study quality in six domains (selection bias, study design, confounders, blinding, data collection methods, withdrawals and dropouts), which can be rated as strong (1 point), moderate (2 points) or weak (3 points) according to a standardized guide and dictionary. The overall rating of study quality can also be classified as strong, moderate, or weak by averaging the scores for the six domain ratings. The two authors independently appraised the quality of each study by using the checklists included in the EPHPP manual. In the occasional case of differing ratings between the reviewers, each explained their reasons for their selection and then for any remaining discrepancies, scores were averaged across the two raters.

Results

Study Characteristics

A total of 12 studies from 11 journal articles were selected for inclusion in the review. All studies were published between 2014 and 2019 and came mainly from Europe (75%). Two were from the USA and one study came from Canada. As presented in Table 2, the studies selected were all experimental or quasi experimental designs but varied in terms of population characteristics, the nature intervention examined and the methods used to assess cognitive outcomes.

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Table 2 Characteristics of studies selected for systematic review

Author, Country	Study Design	n	Sample Characteristics	Intervention	Assessment Time Points	Data Source, Outcome	Main Findings
Amicone et al. (2018), (Study 1), Rome	Quasi-experiment - W	82	Primary public school children, Urban, middle class; 48% female; Mage = 10.1 years	School garden vs built school courtyard; Standardized team play; (30 min)	Immediate post intervention	The Bells Test; (+) Digit Span Forward; (+) Digit Span Backward; (+) Go/No-Go test; (-)	Increase in sustained and selective attention, working memory but not impulse control
Amicone et al. (2018), (Study 2), Rome	Quasi-experiment - B, semi-RCT	36	Primary public school children, Urban, middle class; 47% female; Mage = 10.8 years	School garden vs built school courtyard; Free play; (30 min)	Immediate post intervention	The Bells Test; (+)	Increase in sustained and selective attention
Fägerstam and Blom (2013), Sweden	Quasi-experiment - B	85	High school students; Urban school; % female NR; Age = 13–15 years	Six outdoor lessons in grassed wooded areas vs. mostly indoor lessons with two outdoor lessons; (lessons 60 min each over 8 weeks)	5 months interview and 6 months knowledge test follow-ups	Essay-type question about the biology course content knowledge; (+) for 7 graders (-) for 8 graders(3)	(1) Higher degree of long-term knowledge retention for outdoor classes for 7 graders (2) More vivid descriptions of activities No improvement in understanding of biology
Greenwood and Gatersleben (2016), UK	RCT—B	120	High school students; South West London 55% female;	School grassed area with trees, shrubs, flowers vs. small room with no view of nature; time alone vs. with peer vs mobile phone game; (20 min)	Immediate post intervention	Necker Cube Pattern Control Task (number of reversals); (+)	Better concentration after a break in natural environment vs. indoor environment, especially when being with a friend

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Table 2 (continued)

Author, Country	Study Design	n	Sample Characteristics	Intervention	Assessment Time Points	Data Source, Outcome	Main Findings
Johnson et al. (2019), Canada	Quasi-experiment - B, semi-RCT	71	Children; Halifax urban area; 55% female (experimental) 58% female (control) Age = 8–15 years	Green forested trail vs. built urban area; Walk in small groups of unknown children with a guardian; (30 min)	Immediate post intervention	Combined Attention Systems Test (CAST); Orienting (+) Alerting (+) Others (-)	Results support effects of nature on endogenous attention: Alerting and Orienting, but not on any of the measures of exogenous attention
Li and Sullivan (2016), USA	RCT—B	94	High public school students; urban and rural central Illinois, 56.4% female; NR	Green landscape view vs. built space vs. no window view; Sitting in seats resting with 2 examiners in the room; (10 min)	During intervention, class activity (30 min)	Digit Span Forward & Digit Span Backward (+)	(1) Increased attention in the green view vs. no green window condition (2) Stress reduction did not mediate nature effect
Mygind et al. (2018), Denmark	Quasi-experiment - W	47	Primary school children accustomed to OE; affluent areas; 38% female;	Grassed area with trees vs. classroom environment airy or dark; Reading quietly; (60) minutes	During intervention, testing time (20 min) to be added	D2-R Test (-)	(1) No effect of nature on superior cognitive performance (2) Higher tonic vagal tone in natural environments vs. classrooms
Stevenson et al. (2019), Denmark	Quasi-experiment semi-RCT - W	33	Children from an independent school; 61% female; Age = 10–14 years	Grass fields, tracks with young pine trees, rocks, farmland, forest; vs. urban area Contemplative walk in small groups of 4–5; (30 min)	Immediate post intervention	The Attention Network Task (ANT, fish flanker task); Speed (+) Consistency (+) Executive (-)	(1) Faster, more stable responses on ANT after intervention (2) Greater number of eye fixations per minute (3) No improvements in executive attention or accuracy

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Table 2 (continued)

Author, Country	Study Design	n	Sample Characteristics	Intervention	Assessment Time Points	Data Source, Outcome	Main Findings
van den Berg et al. (2017), The Netherlands	Quasi-experiment - B	170	Primary school children; non-deprived; 43% female Mage = 9 years	Green wall with living plants vs. no green wall in a classroom; Breathing exercise looking at the green wall vs. with closed eyes; (a short time)	During intervention, testing time (20 min) to be added to 2 & 4 months follow-up times	Digit Letter Substitution Test; (-) Sky Search Task; (+)	Increased selective attention in the green wall vs. with no green wall condition; No effect on processing speed
van Dijk-Wesselius et al. (2018), The Netherlands	Quasi-experiment - B, W	2031	Primary school children; moderate-to-high-urbanized areas; just over 60% female; Age = 7–11	Schoolyard with trees flowers, sand, water, grass, hills, bushes vs. paved schoolyard; Active recess time; (15 min)	Immediate post intervention to be added to 1 & 2 years follow-up times	Digit Letter Substitution Test; (+) Sky Search Task; (first follow-up-trend only, p = .08), second follow-up (+)	Positive effect of Greening of Schoolyard on processing speed and trend on selective attention after school recess at second follow-up
Wallner et al. (2018), Austria	Quasi-experiment - W	64	High school students; Chosen from 3 schools in Vienna; 50% female; Age = 16–18 years	Forest vs. large park with trees vs. small urbanized park; Walk with class children; (60 min)	Post intervention and 20 min distance to school	D2-R test (+)	Sustained/Selective attention improvement after the break in all three green spaces, especially medium park
Wells et al. (2015), USA	RCT—B	64	Primary school children; Low income, from rural to urban; Age = 6–12 (at baseline)	Raised-bed garden kit vs. no kit; 19 garden vs. indoor lessons on nutrition, plant science, and horticulture	1 & 2 years follow-up	Science knowledge measured by 7-item questionnaire on nutrition and plants (+)	Positive effect of school garden intervention on knowledge retention, especially for high fidelity garden intervention

W—within-subjects design, *B*—between-subjects design, *RCT*—randomized control trial; (+) significant positive result, (-) not significant result

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Study designs included three randomized and three semi-randomized controlled trials, with most of them being between-subject designs and one a semi-randomized study adopting a within-subject design. The remaining studies were quasi-experimental (within-subject = 3, between-subject = 3). A variety of statistical analyses were applied across studies, including ANOVA, ANCOVA, t-tests and F statistics. Sample sizes were generally adequate but varied substantially across studies ranging from 33 to 3,061 participants. The methodological quality of the studies was assessed as outlined in the method section. Table 3 shows the quality ratings according to each domain of assessment and a global quality rating and classification for each study.

Ratings indicate 83% (10/12) of the studies received a classification of strong (falling within the 1.0–1.50 range) and 17% (2/12) received ratings of moderate (falling within the range of 1.51–2.50). None of the studies received a "low" classification. This signifies that the studies included in this review were generally of a high standard. The quality of studies was also examined within the specific scoring domains and revealed a tendency of bias to occur mostly in the Study Design and Blinding domains. The remaining four domains, namely the Selection Bias, Confounders, Data Collection and Withdrawals and Dropouts, have been rated as predominantly strong or having negligible chance of bias.

Study populations of the reviewed studies included children and adolescents of different age groups. Four of the studies included high-school students aged 16–18 years, and one study included groups of younger adolescents aged 13–15. School children aged 10–12 were recruited in four studies, and one study comprised a diverse group of adolescents aged between 8–15. The two remaining studies represented the youngest age group, one with participants ranging from 7 to 10 years, and the other, between 6 and 12 years. All studies included male and female participants, and overall, there was a reasonable balance of male and female participants across the selected studies.

Collectively, the selected studies operationalized nature interventions as including a variety of natural environments such as school playgrounds, parks, woodlands, school greenery and indoor environments with plants. The interventions differed in time duration, level of social and physical engagement and degree of greenery involved. Table 2 summarizes the types of nature interventions and the comparison activities used in the selected studies. In terms of time duration of interventions, eight studies used short-term nature exposures (from a few to 60 min), while four studies included long-term exposures in their designs (from 2 months to 2 years).

Various cognitive tests have been used in the selected studies as the outcome variable to capture the possible effects of nature on cognitive functioning. They represent two major groups of tests—attention tests (n = 9) and long-term memory knowledge tests (n = 2). Attention tests can be further distinguished on the basis of the cognitive domain they are mainly designed to capture, even though the cognitive domains often overlap in a test. There are four main types of attention tests evident from the selected studies: (1) working memory tests, like Digit Span Backward, demanding ability to hold and manipulate information in the short-term; (2) selective attention tests, like the Fish Flanker Task, which requires the participant to direct attention to the task while simultaneously ignoring distractors; (3) processing

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Table 3 Methodological quality assessment of selected studies

Author, Year	Selection bias	Study design	Confounders	Blinding	Data collection	Withdrawals and dropouts	Global quality
Amicone et al. (2018), (Study 1)	1	2	2	2	1	1	Strong (1.5)
Amicone et al. (2018), (Study 2)	1	1	1	2	1	1	Strong (1.17)
Fägerstam and Blom (2013)	1	2	2	3	1	2	Mod (1.83)
Greenwood and Gatersleben (2016)	3	1	1	1	1	1	Strong (1.33)
Johnson et al. (2019)	1	2	1	2	1	1	Strong (1.33)
Li and Sullivan (2016)	1	1	1	2	1	1	Strong (1.17)
Mygind et al. (2018)	2	2	1	2	1	1	Strong (1.5)
Stevenson et al. (2019)	2	2	1	2	1	1	Strong (1.5)
van den Berg et al. (2017)	1	2	2	2	1	1	Strong (1.5)
van Dijk- Wesselius et al. (2018)	1	2	1	2	1	1	Strong (1.33)
Wallner et al. (2018)	2	2	1	2	1	2	Mod (1. 67)
Wells et al. (2015)	2	1	1	2	1	2	Strong (1.5)

Domain Ratings: 1 = Strong, 2 = Moderate, 3 = Weak

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speed test, like the Digit Letter Substitution Test, the main goal of which is to process as many items as possible in limited time periods; (4) and the Go/No-Go test intended to measure impulse control (see Appendix Table 7).

Effectiveness of the Nature Interventions

Studies included in this review enabled us to investigate nature interventions on cognitive functioning across different attentional domains as well as on long-term memory knowledge acquisition. First, we will present the findings from the attention tests in four sections: (1) working memory tests, (2) selective attention tests also including tests with varying degrees of sustained/selective attention tests, (3) processing speed and (4) impulse control tests. Then we will present the findings from the long-term memory knowledge tests.

Attention Tests

Most studies in our review applied short-term nature exposures to find possible causal effects on attentional processing. These studies were more consistently able to report attentional processing benefits than studies that used long-term nature exposures in their designs.

Working Memory

Two studies (Amicone et al., 2018; Li & Sullivan, 2016) found a significant positive effect of nature on working memory performance in middle-class public school children in Rome and in both urban and rural high-school students in central Illinois public schools, respectively. Both studies used Digit Span Forward and Digit Span Backward, but the tasks differed on whether participants were to write the digits down (Amicone et al., 2018) or to repeat them verbally (Li & Sullivan, 2016). The Rome study used 30 min active play in a green school playground, while the Illinois study used a window view onto green landscape with two examiners in the room where the participants were seated and resting for 10 min. These studies indicate that relative to control conditions, two different nature interventions (one immersive and one passive) involving different age groups can improve cognitive performance that relies on the ability to hold and manipulate information in short-term (working) memory.

Selective Attention and Sustained/Selective Attention

The main common task in tests designed to measure selective attention is to direct attention towards a target while simultaneously ignoring distractors. Most studies (n = 9) in our systematic review have been designed to measure selective attention; however, they have used five different tests for this purpose. In particular, Combined Attention Systems Test (CAST) and the Attention Network Task (ANT) tests are similar measures based on the fish tanker test where the target fish is presented

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facing left or right and flanked by other fish pointing in congruent or incongruent directions, as a cue or distractor. The task requires respondents to indicate the correct direction of the target fish. Other tests like the Necker Task are also used as measures of selective attention but are notably dependent on visual processing. Likewise, The Sky Search and D-2R tests also rely on visual resources to sustain attention. Hence, caution is required when explaining the causal effect of nature on selective attention as visual processing can be a confounding factor.

Two studies (Johnson et al., 2019 and Stevenson et al., 2019) using similar computer attention tests based on the fish flanker task, reported a significant positive effect on selective attention performance after a 30-min walk in a natural environment with trees. Johnson et al. (2019) found a small positive effect with Canadian children of mixed age between 8 to 15 years old after walking through a forested trail in Shrubie Park. Stevenson et al. (2019) found a positive effect for speed and stability of responses, in children aged 10–14 years recruited from an independent school in Denmark, after walking through rolling grass fields with young pine trees and rocks, farmland and forest. However, no improvement in *executive* attention was found in this study.

Two studies (Amicone et al., 2018, studies 1 & 2) found natural environments, designed as structured green playtime and free play in a school garden respectively, exert a significant positive effect on attention control as measured by the Bells Test in primary public school middle-class children in Rome. The Bells test contains four different sheets with small black drawings of different symbols and the task requires respondents to mark all 35 bells embedded within 280 different distracting symbols. The test is relevant to selective attention control but also requires visual scanning. Greenwood and Gatersleben, (2016) also found a positive significant effect on selective attention for high school students of South West London after spending time in the school grassed area with trees, shrubs and flowers for 20 min. They used the Necker Cube Pattern Control Task to measure attention control.

Impulse Control

One study used an impulse control attention test, as measured by Go/No-Go task, to investigate impulse control after green structured play (Amicone et al., 2018). They found no significant positive effect in middle-class public school children in Rome after playtime in a school garden compared with a built playground.

Regarding Sustained/Selective Attention, four studies reported mixed findings derived from the D2-R—Letter Cancellation Task and Sky Search attention tests. The tests are used to measure selective attention but at the same time they require sustained attention for performance. Each test, respectively, presents rows of similar pictures or letters for the participants to visually scan to spot differences. Nature, designed as the living plants classroom wall, has been found to have a significantly positive effect on sustained/selective attention as measured by the Sky Task (van den Berg et al., 2017) in Dutch primary school children. However, the same attention test used in a longitudinal study by van Dijk-Wesselius et al. (2018), for a similar population in the Netherlands, did not yield significant results until after two years

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of green schoolyard exposure at the second follow-up, reporting only a positive trend at the first follow-up. These two studies differ from previous research in their aim to explore the effects of long-term nature exposures on cognition, rather than short-term ones.

Similar to the long-term studies, Sustained/Selective Attention, as measured by the D2-R—Letter Cancellation Task, was not found to be consistently and positively influenced by short-term nature exposure, indicating that perhaps this cognitive domain may not necessarily benefit from exposure to greenspace, irrespective of the duration of exposure. One study (Wallner et al., 2018) reported a significant positive effect after a 60-min break in a green park or forest relative to a small urban park in high school students in Vienna, but no effect was found in younger affluent Danish children 10–12 years old, after being exposed to a grassed area with trees compared with a classroom environment while reading quietly for 60 min (Mygind et al., 2018).

Processing Speed

Mixed findings have also been reported for long-term nature exposure studies examining processing speed as measured by the Digit Letter Substitution test (van Dijk-Wesselius et al., 2018; van den Berg et al., 2017). For the task participants were instructed to convert randomly ordered digits to letters according to a key and to do so within short periods of time. No significant positive effect was found on processing speed in the living plants classroom wall exposure study in Dutch primary school children (van den Berg et al., 2017). However, a significant positive effect was reported in the Greening of School study in Dutch school children aged 7–11 years (van Dijk-Wesselius et al., 2018). Again, these findings may reflect true inconsistency of nature exposure on processing speed, or the difficulty in establishing causal effect for long-term exposure studies.

Long-term Memory—Knowledge Acquisition

Only two studies in our review applied long-term nature exposures to find possible causal effects on long-term knowledge acquisition, and they were inconsistent in their ability to produce favorable outcomes. Wells et al. (2015) found school gardens to be beneficial for enhanced science knowledge, as compared to classes with no garden intervention in American children aged 6–12 years from low-income rural, suburban and urban schools. In addition to the "knowledge of plant science and nutritional science test," they also measured the degree of intervention fidelity, which provided dose-based data to further support the findings. Accordingly, classes that reported the greatest increases in their science knowledge, by 0.78 on average, were the ones receiving higher dosages of the garden intervention.

Fägerstam and Blom (2013) compared outdoor with indoor learning in an urban high school environment with a traditional curriculum. They measured long-term knowledge acquisition by an essay-type question examining the biology course content, (i.e., on knowledge of ecology and classification), and further assessed the

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academic outcomes by a semi-structured interview. They found greater long-term knowledge retention for outdoor compared with indoor classes for 7th graders. However, no significant effects of nature were found for 8th graders. Additional interview data analysis revealed that, overall, intervention participants reported more vivid descriptions of class activities, which were interpreted as coming from higher positive emotional involvement.

Underlying Mechanisms

The second aim of this review is to investigate potential underlying mechanisms of the nature-cognitive performance relationship. Studies designed to demonstrate the effect of nature on cognitive functioning can also provide additional support for the foundational theories and can help to illuminate underlying mechanisms. These studies may also report beneficial effects of nature on some aspects of well-being that could function as mediators for enhanced cognitive outcomes. However, a full analysis of how nature produces beneficial effects would require more targeted and comprehensive work addressing a broad range of mediators to propose a theory. None of our studies have fully investigated the nature-cognition mechanisms specifically in relation to structured physical activity and social interactions; therefore, with regard to our second goal, we take an exploratory approach.

Our systematic review has captured studies that represent three types of theoretical perspectives, each of which proposes a distinctive but complementary explanation for why nature could benefit cognitive functioning and uses a corresponding measurement approach from which to examine the specific theory (see Tables 4, 5 and 6). Thus, different psychological scales and physiological instruments have been employed in the selected studies to uncover possible underlying mechanisms for the beneficial effects of nature.

In this systematic review some studies reporting positive findings point to perceived restorativeness as an explanation, typically assessed either by the Perceived Restorativeness Scale (PRS) or a self-assessed question/questions. For example, Amicone et al., (2018) in studies 1 and 2 reported beneficial findings and noted that children perceived natural environments to be more restorative as measured by the Perceived Restorativeness Scale. This finding supports the restorative process of nature exposure, particularly when contrasted with immersion in the built environment. Consistent with ART, these two studies demonstrated that restorative processes can occur in nature irrespective of how children choose to engage with it, whether in a structured game or free-play.

Stevenson et al. (2019) reported faster and more stable responses on the Attention Network Task after a green walk relative to an urban walk. They did not however, find any significant difference on executive (goal-directed) performance which is central to ART. Stevenson et al. also used a mobile eye-tracker instrument to measure distribution of eye gaze during exposures. Although for only a small sample, they provided some support for ART reporting higher rates of eye gazing during a nature walk compared to an urban walk, they proposed that through the soft fascination element of nature, participants were visually engaged and wanted to explore

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Table 4 Cognitive performance and other outcomes for studies with the ART framework

Author, Year, (sub-study)	Cognitive performance measures; (Outcome)	Other measures (Outcome)	Findings
Amicone et al. (2018), (1)	The Bells Test; (+) Digit Span Forward; (+) Digit Span Backward; (+) Go/No-Go test; (-)	PRS (+)	1) Increase in sustained & selective attention, working memory but not impulse control (2) Higher scores on PRS for natural environment than built environment
Amicone et al. (2018), (2)	The Bells Test; (+)	PRS (+)	1) Increase in sustained & selective attention (2) Higher scores on PRS for natural environment than the built environment
Johnson et al. (2019)	CAST; Orienting (+) Alerting (+) Others (-)	CNS as control	(1) Improvement on two measures of endogenous attention: Alerting and Orienting, but not on any of the measures of exogenous attention (2) Worse performance after urban walk
Stevenson et al. (2019)	ANT (fish flanker task); (+)	PRS-CII as control Mobile eye tracking (+)	(1) Faster, more stable responding on ANT after nature walk vs. walk in built environment, (2) No improvements in executive attention or accuracy; (3) Natural environment perceived as being more restorative than built environment, (4) Greater number of eye fixations per minute while walking in the natural environment than built environment

PRS—Perceived Restorativeness Scale; *CAST*—Combined Attention Systems Test; *CNS*—Connectedness to Nature Scale (Mayer & Frantz, 2004); *ANT*—The Attention Network Task; (+) significant positive result, (-) not significant result

the scenery, hence the higher rates of eye-gazing, and, presumably, higher levels of restoration.

Johnson et al., (2019) provide support for ART by demonstrating a small but significant improvement on executive attention (referred to as endogenous), measured by CAST. This study found that a walk in a natural environment provided elements needed for restoration of goal-directed attention compared with a walk in an urban environment, however, this study did not include a measure of restoration. No additional support for ART was evident from the study by van den Berg et al., (2017). They provided results on self-reported ability to concentrate as well as on emotional, cognitive and social well-being. These additional measures were

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administered to provide insights into the effects of a green wall in the classroom on sustained/selective processing, as measured by the Sky Search task. Although they found a significant positive effect for selective attention, no underlying mechanism could be suggested since no difference between the groups with and without a green wall was found on self-reported concentration or on well-being. The study intervention involved long-term exposure and was complex in its design. It was mixed with short-term exposure which in itself may not have been effective (i.e., resting with eyes closed for the control group might be more restful than looking at the green wall for the experimental group). Thus, the short-term effect could have interfered with the long-term exposure to the green wall. In sum it would seem that the underlying mechanisms of ART theory were best demonstrated by the studies using short-term nature exposures when mental restoration was needed.

The remaining studies come from research perspectives associated with different pathways as possible mechanisms for the restorative effect of nature on cognitive processes. They propose that other mechanisms apart from mental fatigue restoration could include stress and affect. One of these studies (Li & Sullivan, 2016) provided additional results on self-reported subjective attention and stress, measured by a Visual Analogue Scale (VAS), as well as measures on objective stress, including blood volume pulse, electrocardiography, skin conductance and body temperature. All the data were entered into regression models to provide further insight on possible factors at play to explain their main finding, that is, the effect of a green view on working memory, as measured by digit span tests. Since the analysis revealed no correlation between attention and stress changes, Li and Sullivan (2016) proposed that nature exposure was likely to have a direct impact on working memory performance rather than through the effect of a stress pathway. This study used only 10 min of exposure time, adding to the body of evidence on nature restorative capacities for attentional processes.

Wallner et al., (2018) explored psychological dimensions of well-being for positive effects of greenspaces on concentration performance measured by the D2-R test. They adopted the scale (Nitsch, 1976), which is designed to measure motivation and strain attributes for six categories (recuperation, tension/relaxation, state of mood, readiness for action, readiness for exertion, and alertness) of the Self-Condition Scale. They investigated how motivation and strain could help to explain their main findings and found that large greenspaces resulted in greater cognitive performance alongside several psychological dimensions of recuperation, tension/relaxation, mood state, readiness for action, and readiness for exertion. These dimensions are indicative of a higher degree of restorativeness, as well as psychological and physiological calming. Hence, these may be mediating factors for the effect of nature on cognition, suggesting that the key theories may be inter-connected.

Greenwood and Gatersleben (2016) reported improvement in concentration, as measured by the Necker Cube Pattern Control Task in a natural environment versus an indoor room, in three additional contexts for each condition, being alone, alone with a mobile phone, and being with a friend. They used Zuckerman's (1977) Inventory of Personal Reactions (ZIPERS) as their measure of positive affect, attentiveness, fear, sadness and anger to support their findings, and included objectively measured stress for this purpose as well. They reported a significant interaction

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Table 5 Cognitive performance and other outcomes for studies with the ART and SRT framework

Author, Year, (sub-study)	Cognitive performance (Outcome)	Other measures; (Outcome)	Findings
Greenwood and Gatersleben (2016)	NCPCT (number of reversals); (+)	Heart Rate; (+) Blood Pressure; (-) ZIPPERS; Positive affect (+)	Better concentration after a break in natural environment vs indoor environment, especially in the context of being with a friend
Li and Sullivan (2016)	Digit Span Forward & Digit Span Backward (+)	VAS-self-reported attentional functioning; (+) Physiological stress; (+)	(1) Increased attention in the green view vs. with no green window condition (2) Stress reduction did not mediate the the relationship between window view and attention restoration
van den Berg et al. (2017)	Digit Letter Substitution Substitution Test; (-) Sky Search Task; (+)	Self-reported ability to concentrate; (-) Self- reported emotional state; (-)	(1) Increased selective attention in the green wall vs. with no green wall condition (2) No effect on processing speed (3) No improvement on emotional state
Wallner et al. (2018)	D2-R Test; (+)	Nitsch scale; (+)	(1) Sustained/Selective attention improvement after the break in all 3 green spaces (small urban park, medium park, forest), medium park especially (2) Well-being increased after the stay in the 3 green spaces, but a sustained effect only for the forest condition
Mygind et al.(2018)	D2-R Test; (-)	PHASIC; (+)	(1) No improvement of superior cognitive performance in the natural environments compared to the classrooms (2) Tonic vagal tone was higher in the natural than the classroom environments

NCPCT—Necker Cube Pattern Control Task; *PHASIC*—the difference between tonic and event vagal tone; (+) significant positive result, (-) not significant result

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Table 6 Cognitive performance and other outcomes for studies with the Outdoor Learning (OL) and Greening of Schoolyard framework

Author, Year	Cognitive performance measures; (Outcome)	Other measures Outcome)	Findings
Fägerstam and Blom (2013)	An essay-type question on biology course content	Semi-structured interviews for cognitive and emotional dimensions (+)	(1) Higher degree of long-term knowledge retention for outdoor vs. indoor classes for 7th Graders (2) No difference in biological understanding (3) More vivid descriptions of activities
van Dijk-Wesselius et al. (2018)	Digit Letter Substitution Test; (+) Sky Search Task; (trend only, p = .08)	Appreciation of the Schoolyard; (+) PRCS; (-), (+) PQLS; (-)	(1) Positive effect of Greening of Schoolyard on processing speed and trend on selective attention after school recess at second follow-up (2) Positive impact on appreciation of the schoolyard (3) Some short-time positive impact of Social Orientation for younger children and negative impact for older children (4) Some support of greening on self- reported peer problems (5) No impact of greening on emotional functioning (6) Impact on time spent outdoors only for girls at first follow-up
Wells et al. (2015)	Science knowledge measured (7-item questionnaire on nutrition and plants)	GIF as control	Positive effect of school garden intervention on knowledge of plant science and nutritional science, especially for high fidelity garden intervention

PRCS - Perceived Restorative Components Scale; *PQLS*-Pediatric Quality of Life Scale; *GIF*- Garden Intervention Fidelity; (+) significant positive result, (-) not significant result

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effect for positive affect in a natural environment compared with an indoor room. This supports a biophilic response whereby nature feels both good and familiar. In addition, Greenwood and Gatersleben (2016) analyzed the role of social relations in the nature-cognition relationship. They concluded that even though improvements on the Necker Cube Pattern Control Task were observed across all contexts in the natural environment, for this particular age group of 16–18 year olds, nature appears to be especially restorative if it is undertaken with friends.

The social aspect is also a possible mediator in a longitudinal study on greening a schoolyard (van Dijk-Wesselius et al., 2018). In the second follow-up, after two years of exposure to a green schoolyard, children reported scoring significantly better on sustained/selective attention and processing speed compared to children with paved schoolyards. Self-reported questionnaires on aspects of well-being were also analyzed alongside the main results and a green schoolyard was found to benefit social well-being. By comparison, no improvements on emotional well-being were found. Children's appreciation of the green schoolyard was suggested as an additional possible mediating factor, perhaps pointing to natural order and beauty as playing a bigger role than just purely aesthetic. As it is usually difficult to establish a direct effect of long-term nature exposure on cognitive functioning, many possible indirect mediators are possible.

Mygind et al. (2018) investigated the impact of nature on cognition in terms of the Stress Reduction Theory (Ulrich, 1983). They used tonic and phasic cardiac vagal tone for this purpose. Tonic vagal tone enables the modulation of the vagus nerve which fosters a calming effect on heart rate during rest and is linked with greater adaptability to external factors (Mygind et al., 2018). As predicted, they found that tonic vagal tone (but not event or phasic vagal tone) was higher in the natural environment than in indoor classrooms, but no significant difference was observed on the D2-R attention test in these two conditions. This increase in tonic vagal tone may lend some weight to the SRT.

Finally, the two remaining studies in our review (Fägerstam & Blom, 2013; Wells et al., 2015) align with the outdoor learning perspective—a body of research that mainly focuses on long-term knowledge acquisition rather than attentional functioning (Becker et al., 2017). Depending on the specific theory prescribing outdoor learning, studies may either attempt to explain psychological/physiological internal processes during learning out in nature or be more practical and explain in detail what aspects of the intervention appear to be most effective.

Wells et al. (2015) examined the effects of a school garden intervention on science knowledge, specifically on nutrition and plant science. A significant effect of garden lessons relative to indoor lessons, on science knowledge was found especially for interventions with high garden intervention fidelity. Fidelity was examined to provide details about how specific aspects of garden learning interventions contribute to the program's success. Wells et al. (2015) found that higher intervention fidelity involved greater dosage of outdoor garden classes as well as having more success at growing and sharing fruits and vegetables. However, the study did not provide sufficient empirical evidence on underlying mechanisms such as how longer exposure to garden lessons might affect knowledge acquisition. Another outdoor learning study (Fägerstam & Blom, 2013) investigated children's internal thoughts and emotions about the intervention using interviews, to further explain

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the main findings. The outdoor group described their outdoor lessons more clearly, used content-related words and showed more enthusiastic and participatory behavior compared with the indoor group. However, only children in Year 7, and not Year 8, demonstrated a significant improvement in their content knowledge, as measured by the biology essay-type questions. Hence, there is some uncertainty about how, or if, children's emotions might contribute to the nature-cognition relationship and the significance of age on this relationship.

In sum, it would seem that the nature studies included in this review support a multitude of underlying factors influencing the nature-cognition relationship. However, the restorative factor is the one that has been most commonly tested with the use of specific self-report restoration measures such as the Perceived Restorativeness Scale. It is noteworthy however, that this measure includes items assessing dimensions such as relief from daily stressors and strains, feeling relaxed, free movement and curiosity. Hence, restoration can extend beyond cognitive relief to also include physical and psychological aspects. In particular, the increased physical activity and social interaction typically associated with outdoor learning may also be influencing factors (Becker et al., 2017). This lends weight to the possibility that multiple underlying factors might be at play potentially producing a synergistic impact as suggested by Kuo et al., (2019).

Effects of Nature interventions and the Influence of Age

The third aim of our review was to investigate possible differences of nature exposure effects on cognitive functioning for children of different age groups. Greenspace exposure does not seem to differentially effect child and adolescent cognitive functioning as it is generally beneficial for all age groups covered in this review. For high school students, however, the effect of greenspace on attentional functioning is found more consistently (Greenwood & Gatersleben, 2016; Li & Sullivan, 2016; Wallner et al., 2018) indicating that older children can benefit from a variety of nature interventions irrespective of whether it is a window view of nature, a walk in a park, or spending time playing in nature. These studies have shown that working memory, as well as selective and sustained attention, improve for high school students after green exposure, compared with urban exposures. For long-term knowledge acquisition the effect of nature produces mixed results with this older age group. Fägerstam and Blom (2013) found that outdoor lessons can improve students' knowledge retention on biology for a seventh grade group but not for the eighth graders. Wells et al., (2015) found that across a diverse age range (6–12 years) experiential garden-based lessons on nutrition, horticulture and plant science resulted in significantly better knowledge retention assessed using a multiple-choice test, relative to those who completed classroom-based lessons.

Similar patterns for attentional functioning have been found in other age groups. For younger, mostly secondary school children, there is evidence that children can benefit from nature exposure in terms of working memory as well as selected and sustained attention (Amicone et al., 2018; Johnson et al., 2019; Stevenson et al.,

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2019) after a walk or play in a natural compared with urban environment. The remaining studies focusing on secondary school children (Amicone et al., 2018; Mygind et al., 2018) examined two additional attentional domains, namely, impulse control and selective/sustained attention, with an emphasis on visual scanning and processing speed, as measured by the Go/No-Go and D2-R tests, respectively. No observed significant positive effects of nature exposure were found in these studies. Finally, for the youngest group of school children (aged 7–12 years), nature exposure does not show similar patterns of effect in cognitive functioning as for middle and high school children. Had there been more experimental studies focusing on young children, perhaps a pattern could be established. Wells et al., (2015) have provided evidence that 6–12 year old children can benefit from a school garden intervention in terms of long-term knowledge retention on plant and nutritional science compared to children with no garden activity lessons. This finding adds to the body of research in nature exposure on long-term memory retention, but further work is needed since mixed results have been reported for older groups of children. With respect to attentional processes in young children, the effect of nature exposure on selective/sustained attention and information processing speed has produced mixed results (van den Berg et al., 2017; van Dijk-Wesselius et al., 2018).

Study duration

As can be seen from Appendix Table 8, most interventions used in the studies reviewed were of a short duration and focused on attentional functioning as an outcome. Five studies used immediate post-intervention designs with a time range of 20–30 min (Amicone et al. (study 1 and 2), 2018; Greenwood & Gatersleben, 2016; Johnson, et al., 2019; Stevenson, et al., 2019). These studies were most consistent in reporting positive effects of nature exposure, in particular, on selective attention, working memory, concentration, alerting, orienting and speed, with exception of impulse control (Amicone et al. (study 1), 2018), exogenous attention (Johnson, et al., 2019) and executive attention (Stevenson, et al., 2019).

The remaining short-term exposure studies used post-intervention designs and during intervention designs (10 to 60 min) (Wallner et al., 2018; Li & Sullivan, 2016; Mygind, et al. 2018). Our review supports the effectiveness of short-term nature interventions to improve attentional functioning. However, mixed results were reported on sustained/selective attention, namely, positive effects were reported by Wallner et al. (2018), and no effects were reported by Mygind et al. (2018).

Four studies in our review applied longer-term exposures in their designs (Fägerstam & Blom, 2013; Wells et al., 2015; van Dijk-Wesselius et al., 2018; van den Berg et al., 2017). Specifically, there were two experiments (Fägerstam & Blom, 2013; Wells et al., 2015) that examined whether exposure to natural environments influenced knowledge retention over longer-time periods (5 and 6 months, 1 and 2 years follow-up). Both studies examined outdoor education in school-settings. Wells et al. (2015) provided support for benefits of outdoor education in school settings for primary school children, Fägerstam and Blom (2013), however, reported benefits for 7th graders but not for 8th graders.

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The remaining two studies (van Dijk-Wesselius, et al., 2018; van den Berg, et al., 2017) examined long-term nature exposure (2 and 4 months, and 1 and 2 years, respectively) on attentional functioning rather than long-term knowledge. The studies were complex in their design and provided mixed findings of nature exposure on selective attention and processing speed. For example, the green wall study (van den Berg, et al., 2017) was designed to measure attentional functioning after a short-time exposure of looking at the classroom green wall (a few minutes), just before testing. In addition, this short exposure was also combined with longer-term exposures of 2 and 4 months, accumulating during the time children were studying in the green wall classroom. So, it is difficult to disentangle short-term effects from long-term effects. Similarly, van Dijk-Wesselius, et al. (2018) used 1 and 2 years of long-term exposures to school greenery and reported beneficial effects on processing speed at the second follow-up. However, the testing was administered after school recess, again adding a short-term exposure as a possible effect.

Discussion

The primary aims of this review was to (1) systematically evaluate the body of experimental and quasi-experimental studies examining the effect of nature (greenspace) on cognitive functioning in children and adolescents; (2) to investigate the underlying processes involved in possible effects of nature on cognitive performance and to consider the adequacy of different theoretical models to explain any effects; and, finally to, (3) examine whether the effects of nature exposure differ according to age. In addition, possible differences in relation to the duration and type of nature intervention were examined. This review found that based on 12 relatively high-quality studies, there seems to be substantial evidence that exposure to nature can enhance cognitive functioning in children and adolescents. This review included an examination of a range of cognitive functions relating to attention and knowledge acquisition including working memory tests, selective attention tests (also including tests with varying degrees of sustained/selective attention tests, processing speed), impulse control tests and long-term memory (knowledge acquisition). Many positive effects were found especially across the sub-categories of working memory and sustained/selective attention. There were only three studies focusing on processing speed (n = 2) and impulse control (n = 1) and the findings of these were less favorable. These findings suggest that key cognitive processes relating primarily to attention and memory (working and long term) were enhanced following nature exposure. This was irrespective of the actual nature intervention being delivered (e.g., playing outdoors in greenspace, observing nature from a window or gardening). As all the included studies were of a high (n –10) or moderate standard (n = 2) using the EPHHP, the findings hold firm and have practical implications for learning environments with young people. Integrating nature interventions with teaching and learning practices can provide welcome cognitive relief for highly anxious young people feeling the pressures of academic performance and testing. Simply learning amidst nature and short-term nature interventions can have beneficial cognitive effects particularly for high school students.

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This review also explored what the underlying mechanisms might be for nature exposure to lead to favorable cognitive outcomes for school aged children. There was substantial support for the restorative effects of nature on cognitive functioning. This was ascertained by improved attentional functioning after nature exposure, relative to being amidst built environments, as well as by self-reported accounts about how replenished the students felt after nature exposure. This is consistent with ART and previous studies such as van den Berg et al. (2016) who found that children reported feeling restored after being in nature. While stress reduction, relaxation and well-being were also reported as outcomes in a variety of studies, thus supporting SRT and the biophilia hypothesis respectively, the findings were not always consistently favorable for all outcomes. For example, Greenwood and Gatersleben (2016) found that participants improved their concentration, positive affect and heart rate after a break outdoors in nature (compared with an indoor condition) but their blood pressure did not improve. Interestingly, this study also found that the effects of nature on positive affect were strongest when participants were with a friend as opposed to being alone. Studies like this suggest that there may be a synergistic effect of numerous mediating factors as well as the potential for confounding factors such as social interaction, to contribute to the benefits. In addition, the ability to examine underlying mechanisms depends on the measures selected for the studies and the reliability and validity of these measures to accurately detect change. For example, it may be that certain physiological indices are more sensitive measures of change than others (e.g., heart rate compared with blood pressure) or that subjective experiences may be easier for researchers to measure than physiological outcomes. It is important in the future to design a priori nature studies that can effectively test the relative contributions of theories and mediating factors. This review has identified some likely contributors but a better understanding of the combination of factors that are most conducive to nature benefits will have positive implications for practice and achieving desirable outcomes for cognitive functioning and well-being.

Along these lines, the active or passive role nature plays in exposures may be an important factor to consider when examining cognitive outcomes of nature interventions. The scope of this review does not allow different mechanisms related to types of involvement in nature exposure designs to be identified; however, it would be worth knowing if different forms of engagement with nature lead to different cognitive outcomes. If we use Norwood's (2019) definition of active/passive engagement with nature, most of the included studies in our review used passive rather than active nature exposure as the intervention treatment, that is, nature was used as a background for other activity like walking, active play and sitting quietly while reading. In contrast, in two outdoor education studies (Fagerstam & Blom, 2013; Wells et al., 2015) nature played a central role. In the remaining studies, nature may be argued to have played somewhat of an active role. One study involved a green walk with a series of added short talks to contemplate on nature (Stevenson, Dewhurst, Schilhab, & Bentsen, 2019), and another study (Amicone et al., 2018, study 2) used free play in the garden with the intention of shifting children's attention from an activity of a regular group game. Finally, the green wall study (van den Berg et al., 2017) used living plants designed as a visual focus during the rest period, as a short-term exposure, which would make it an active use of nature. However, the study

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also involved a long-term exposure to the green wall in its follow-up, which would make it a passive type of exposure.

The issue of passive/active role nature plays in exposure designs to explain underlying mechanisms in nature-cognition relationship often overlaps with active/passive involvement of participants themselves in how they use the natural environment. The underlying mechanisms may be similar. The nature exposure may facilitate physical activity (e.g., walking or playing in a garden) or simply involve being passive around nature (e.g., looking at nature from a classroom window). It appears that for younger students in primary school, physical activity in nature is common and beneficial. Benefits may be partly due to the physical development and coordination that occurs for young people during this age and their innate drive to play and explore (Fjørtoft, 2004). For high school students, nature exposure effects occurred with as well as without physical involvement—this is a promising finding given that adolescents tend to be at high risk of mental illness and can experience high levels of anxiety (Tiller et al., 2020). A limit to understanding how nature differentially affects children at various ages, is that the focus of the experimental studies has been on high school students. More high-quality research is needed with primary school students, particularly in the early years. Moreover, considering that studies report on various cognitive domains and that they differ substantially in design, study population and nature exposure, the comparison of subgroups is highly restricted. There are also additional differences on how the studies apply statistical adjustments for demographic and socio-economic confounders.

Despite a lack of consistency in findings on long-term nature exposure benefits for cognitive functioning, one should not dismiss positive findings in the area of greening or outdoor education interventions used in short-term school settings. Studies on everyday exposure to greenness for all age groups provide insight into the methods of reducing attentional difficulties and the ways to support academic development (Faber Taylor and Kuo, 2011; Tallis, et al., 2018; Wu et al., 2014). In consideration of education becoming increasingly important for children, particularly as they spend more time in the school environment when they progress through primary, middle and high school levels, more research is focused on school surrounding greenness (Li, et al., 2019; Matsuoka, 2010). Li, et al. (2019) measured greenness as tree cover density and reported a positive association with adolescents' academic performance. More sophisticated measurement of school greenness was applied in Matsuoka's (2010) study to examine how particular nature features around school buildings would be best associated with students' grades. Student performance was positively associated with greater quantities of trees and shrubs, particularly as viewed from their cafeteria. Conversely, large area features like parking lots, campus lawns and athletic fields were negatively related to academic performance.

Hence, greenspace exposure seems to be correlated with children's and adolescents' cognitive functioning in different ways depending on their developmental level. Further investigation of long and short-term effects of well-defined nature exposure over the child's life course has the potential to provide guidance for parents and school leaders on how nature exposure may help students better engage with their learning or improve their overall academic achievement. While research indicates nature exposure benefits across a child's life span, more attention should

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be given to identifying specific greenspace features for well-defined and diverse populations. For example, it may be useful to distinguish children with mild symptoms of attention disorders from those with severe symptoms. Findings from Faber et al.'s (2011) study indicate that relatively open grass settings could better alleviate attention symptoms for hyperactive children than settings with trees and grass. School-based short-term interventions may play an important role in self-regulation issues as it is important in everyday school tasks and essential for effective attention functioning (McClelland, et al., 2010). Correspondingly, direct attention—described in ART theory as having limited mental resources and requiring restoration—would equally benefit from nature exposure. Children are being challenged with increasing cognitive demands and nature exposure can be restorative for each age group in different ways. To establish exactly how this occurs, precise descriptions of nature exposure are required. Furthermore, measurements of cognitive functioning should be sensitive enough to detect meaningful differences across the child and adolescents' age span so that age-appropriate nature strategies can be developed.

Strengths, limitations and implications

The high quality of studies included in this review is a strength. This was examined using the EPHPP which assessed six domains (selection bias, study design, confounders, blinding, data collection methods, withdrawals and dropouts). Ratings were conducted by both authors with near perfect consistency, indicating that 10 of the 12 studies adhered strongly to quality standards and two moderately to quality standards. The main areas of bias occurred mainly in the study design and blinding domains. This is not surprising for nature interventions with ecological validity, where blinding is not really feasible. Another limiting factor concerns the suitability of the comparison group. While it can be argued that greenspace interventions can be compared with alternative conditions that are commonly used in schools, if the comparisons are barren concrete areas like car parks, then the relative benefits of greenspace would not be surprising. Comparing greenspace with other spaces that are aesthetically pleasing, such beautifully designed buildings would make a fairer comparison. Overall, however, the high quality of studies included in this review provide confidence in the findings obtained and the case for investing in nature interventions for improved cognitive health and well-being, particularly for school children.

Our main objective was to establish if the causal effects of nature on cognitive functioning could be demonstrated experimentally in variety of settings involving both short-term and long-term cognitive outcomes. However, this objective presents a challenge to explain precisely how the process occurs. A closer analysis would require refinement of the definition of nature exposure itself. Norwood et. al. (2019) advocate the need to isolate the role of nature exposure in research away from possible confounders. For example, nature exposure in adventure or wilderness therapy is an integral part of such interventions and they use nature in an active way alongside the counselling process itself. For this purpose, they define passive nature exposure

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in an attempt to remove it from possible factors like social engagement. Such passive exposure may "take place in a natural environment which itself is not actively integrated or consciously used in an activity" (Norwood et. al., 2019, p.72).

The studies in this review were not designed to examine nature exposure in its pure form that would eliminate the influence of other possible variables, such as being with other people or engaging in various types of physical activity, and they differ in the degree of passive/active use of nature in their exposure settings. The selected studies also focused on real-world settings, including potential confounders such as social interaction and physical activity (see Appendix Table 8 for passive/active dimension of interventions).

Thus, a strength of this review lies in the inclusion of a variety of types of nature exposure in terms of duration and settings to demonstrate causal effect of greenspace on cognitive functioning. However, because of the wide inclusion criteria it was difficult to determine the exact mechanism of impact. Although further analysis of short-term and long-term exposures allowed for identifying factors described in ART theory on attentional processing, there was not enough evidence for explaining mechanisms involved in long-term nature exposures (see Appendix Table 8 for short-term/long-term duration of interventions).

Similarly, this review includes a variety of outcome measures. Some of them are used in a traditional school environment, others, coming from laboratory test settings. This wide inclusion criteria on our outcome measurement is a strength as well as a limitation. Comparing different outcome measures limits generalizing to overall cognitive functioning. However, a wide range of possible cognitive benefits provide an opportunity to further explore the greenspace-cognition relationship. The majority of outcome tests adopted in the included studies are of particular interest. They relate to attentional functioning such as direct attention, selective attention and also mental processing involving tedious activities. These mental functions are in constant demand in school classrooms (Diamond & Taylor, 1996) and require frequent restoration. The studies included in our review show how to restore attention through short-term exposure to nature to maintain students' focus and optimal attentional functioning. We also included studies with traditional outcome measures of academic performance that are mainly designed to examine possible long-term effects of nature exposure. Our findings suggest that employing both types of nature exposures can be beneficial. The short-term nature breaks would maintain basic healthy attentional functioning in the classroom and, at the same time, long-term nature exposure is recommended to provide a supportive environment for other restorative aspects of students' functioning, including social, physical and mental dimensions. Further research is required to identify the exact underlying mechanisms of long-term nature interventions involving holistic approaches to student functioning.

Another limitation is the narrow range of geographical areas of the papers included in this review, with different climates and cultures. Greenness as measured by NDVI most often excludes other colors that are part of nature. For example, autumn color foliage has been perceived as especially restorative by elementary school children when compared to green foliage (Paddle & Gilliland, 2016). The findings indicate that greenspace measures should expand to include orange and perhaps other colors that we can find in high mountainous areas or deserts.

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Recommendations for Future Research

A number of design issues warrant attention in experimental studies of nature exposure on cognition. Nature exposure needs to be well described at every stage of the experiment for both short-term and long-term studies. For example, studies that are designed to examine short-time effects of nature on attentional functioning should also be accounting for long-term exposure to the natural environment (like surrounding school, neighborhood, or home greenery) with the same scrutiny as socio-economic status is routinely checked in many studies. Correspondingly, for long-term studies, most often measuring surrounding greenness, the testing environment itself also needs to be described, with special consideration given to any natural green features (e.g., does the testing room have windows with green views, or is there a living plant in the area?).

There is also the issue of lack of consistency between nature exposure experiments of pre-exposure activities. For example, studies in school settings may have specific classes like maths or art before testing. These classes need to be described as they may vary in the extent to which they are cognitively demanding. Likewise, for long-term exposure studies examining for example, school greenness on academic performance, pre-testing conditions like their environment on the way to school, need to be accounted for. For example, some students may need to walk through busy urban streets to get to school for an exam, while some may be walking through a park. Thus, pre-testing conditions need to be accounted for in most experimental designs in order to control possible differences in nature exposure effects.

Conclusion

The positive findings from this review are heartening given the modern-day pressures faced by many young people in westernized society (Blake et al., 2018; Michaelson et al., 2020; Vancampfort et al., 2018) including the pressure to perform well academically (Tiller et al., 2020). The diminishing opportunities for nature exposure, and immersion in the technology saturated lives of young people, heighten the importance of embedding nature in the everyday experiences of young people to enhance mental health (Capaldi et al, 2015; Diaz et al., 2015; Hartig et al., 2014). Hence, exposure to nature during school time is ideal. The findings that short-term active and passive nature interventions were effective for promoting cognitive functioning makes the integration of nature into school life feasible. It is also worthwhile given that nature exposure facilities cognitive qualities such as attention, memory and knowledge acquisition that are conducive to learning (Mason et al., 2021). Urban planners and educators need to consolidate efforts to create a range of short and long duration nature interventions including school yard greening, internal greening, classroom views of nature and curriculum focused on biology, horticulture, sustainability and biodiversity. Preliminary findings suggest this would create a physiologically calming and restorative environment conducive to improved attention and knowledge acquisition—both of which are essential for learning. Support for school-based exposure to nature is growing and this systematic review focusing on high quality experimental studies, has contributed to a tipping point of evidence favoring the dissemination of nature interventions for enhanced cognitive functioning with children and adolescents.

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Appendix

Table 7 Attention performance tests by cognitive domains

Attention performance measures; Author (substudy); (Outcome)	Domain of cognition	Test Description
Digit Span Forward Digit Span Backward; Amicone et al. (1); (+) Li and Sullivan); (+)	Working memory—performance relies on the ability to hold and manipulate to-be remembered information in the short-term to enable goal directed behaviour	A series of digits given in longer lists (from 2 to 6 digits) if done successfully until two subsequent fails. The task in the Digit Span Forward – to recall the digits in the same order presented. The task in the Digit Span Backward – to recall the digits in the reverse order
The Bells Test; Amicone et al. (1); (+) Amicone et al. (2); (+)	Selective attention, sustained attention—the need to direct attention towards a target while simultaneously ignoring distractors	The test—four different sheets with small black drawings of different symbols (house, tree, bird, bell, etc.). The task – to mark all the 35 bells embedded within 280 different distracting symbols
CAST; (fish flanker task); Johnson et al.; Orienting (+) Alerting (+) Others (-)	Selective attention, orienting, alerting – the test requires directed attention on mainly visual stimuli and also auditory stimuli	Computer test—the target fish is presented alone or surrounded by a school of fish (flankers) that are facing in either the same or opposite direction of the target fish. The variables manipulated in the task are: target fish direction (left vs. right facing), location (left vs. right); flankers (none, congruent incongruent); auditory and visual cues. The task – indicate the correct direction of the target fish
ANT; (fish flanker task); Stevenson et al.; (+)	Selective attention—(1) executive attention score (EXE) as an index of directed attention ability; (2) standard error of RT on all correct trials (SERT); 3) mean RT on all correct trials (mRT); (4) total accuracy (ACC)	Computer test – The target fish is presented centrally facing left or right and is flanked by other fish pointing in congruent or incongruent directions. The variables manipulated in the task: spatial cue (cue vs. no cue, cue vs. neutral cue). The task – indicate the correct direction of the centrally located target fish

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Table 7 (continued)

Attention performance measures; Author (substudy); (Outcome)	Domain of cognition	Test Description
NCPCT (number of reversals); Greenwood and Gatersleben; (+)	Selective attention, concentration on visual stimuli. The test requires directed attention to hold one perspective of the cube for as long as possible	The test – a drawing of 3D cube image which may be perceived from alternative perspectives. The task – to focus on one perspective for as long as one could and tap on the table every time the pattern shifts
Sky Search Task; van den Berg et al.; (+) van Dijk-Wesselius et al.; (trend only)	Sustained/selective attention – visual scanning, the test also requires the ability to attend to relevant visual stimuli while ignoring irrelevant stimuli	The test – an A4 paper with rows of pictures of identical or different spacecraft pairs. The task – to underline identical pairs in 40 s. Different versions of the test with different spacecrafts' configurations are used at each time of measurement
D2-R Test; Wallner et al.; (+) Mygind et al.; (-)	Sustained/selective attention, visual scanning speed, processing speed, concentration, the test also requires the ability to attend to relevant visual stimuli while ignoring irrelevant stimuli	The test – 14 rows of "d" and "p" letters with one, two or three marks. The task—to identify and cross out the letter "d" with two apostrophes in each row and and to move on to the next row after every 20 s periods
Digit Letter Substitution Test; van den Berg et al.; (-) van Dijk-Wesselius et al.; (+)	Information processing speed	The test – randomly ordered digits (1–9) with a key that assigns a letter (L, H, Y, N, R, E, D, T, S) to each number. The task—to convert randomly ordered digits to letters according to the key within 90 s. Different versions of the test with different keys
Go/No-Go test; Amicone et al. (1); (+)	Impulse control—the test requires one to process auditory stimuli to respond with action or inaction to demonstrate the capacity to inhibit a dominant response	The test – a sheet with 20 items, each item composed a drawing of a "path" made up of 14 squares. The task – to respond to the "go" and "no-go" sounds by either dotting the square or not making the move on the path

CAST—Combined Attention Systems Test; *ANT*—The Attention Network Task; *NCPCT*—Necker Cube Pattern Control Task

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Table 8 Intervention duration by active/passive dimension

Author, Year, (sub-study)	Cognitive performance measures; (Outcome)	Other measures (Outcome)	Passive/Active
Nature exposure time from 20–30 min for immediate post intervention designs			
Amicone et al. (2018), (1)	The Bells Test; (+) Digit Span Forward; (+) Digit Span Backward; (+) Go/No-Go test; (-)	PRS (+)	Passive (30 min active play)
Amicone et al. (2018), (2)	The Bells Test; (+)	PRS (+)	Passive and a possibility of Active (30 min free play)
Greenwood and Gatersleben (2016)	NCPCT (number of reversals); (+)	Heart Rate; (+) Blood Pressure; (-) ZIPPERS; Positive affect (+)	Passive (20 min alone vs. with a friend vs. phone game)
Johnson et al. (2019)	CAST; Orienting (+) Alerting (+) Others (-)	CNS as control	Passive (30 min walk)
Stevenson et al. (2019)	ANT (fish flanker task); (+)	PRS-CII as control Mobile eye tracking (+)	Passive with a possibility of Active (30 min contemplative walk)
Nature exposure time of 60 min for post intervention designs (+ 20 min)			
Wallner et al. (2018)	D2-R Test; (+)	Nitsch scale; (+)	Passive (60 min walk + 20 min drive)
Nature exposure time from a few to 60 min for during intervention designs (+ activity time)			
Li and Sullivan (2016)	Digit Span Forward & Digit Span Backward (+)	VAS-self-reported attentional functioning; (+) during 30 min class Physiological stress; (+)	Passive (seated and resting for 10 min activity)
Mygind et al. (2018)	D2-R Test; (-)	PHASIC; (+)	Passive (reading quietly plus 20 min testing time)

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Table 8 (continued)

Author, Year, (sub-study)	Cognitive performance measures; (Outcome)	Other measures (Outcome)	Passive/Active
Long-term nature exposure from 2 months to 2 years			
Fägerstam and Blom (2013)	An essay-type question on biology course content	Semi-structured interviews for cognitive and emotional dimensions (+)	Active (outdoor lessons over 8 weeks, measured at 5 and 6 months)
van den Berg et al. (2017)	Digit Letter Substitution Substitution Test; (-) Sky Search Task; (+)	Self-reported ability to concentrate; (-) Self- reported emotional state; (-)	Active (few minutes of viewing the green wall), Passive (2 and 4 months of using the classroom with the green wall)
van Dijk- Wesselius et al. (2018)	Digit Letter Substitution Test; (+) Sky Search Task; (trend only, p = .08)	Appreciation of the Schoolyard; (+) PRCS; (-), (+) PQLS; (-)	Passive (recess time in school green area for 1 and 2 years)
Wells et al. (2015)	Science knowledge measured (7-item questionnaire on nutrition and plants	GIF as control	Active (19 garden lessons, measured at 1 and 2 years)

PRS—Perceived Restorativeness Scale; *NCPCT*—Necker Cube Pattern Control Task; *ZIPPERS*—the ZIPPERS emotional restoration; *CAST*—Combined Attention Systems Test; *CNS*—Connectedness to Nature Scale; *ANT*—The Attention Network Task; *ZIPPERS*—the ZIPPERS emotional restoration; *PHASIC*—the difference between tonic and event vagal tone; *PRCS*- Perceived Restorative Components Scale; *PQLS*-Pediatric Quality of Life Scale; *GIF*- Garden Intervention Fidelity

(+) significant positive result, (-) not significant result

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Residential greenness and prevalence of major depressive disorders: a cross-sectional, observational, associational study of 94 879 adult UK Biobank participants

Summary

Background Increased urbanisation and the associated reduced contact of individuals with natural environments have led to a rise in mental disorders, including depression. Residential greenness, a fundamental component of urban design, has been shown to reduce the public health burden of mental disorders. The present study investigates the association between residential green exposure and prevalence of major depressive disorders using a large and diverse cross-sectional dataset from the UK Biobank.

Methods In this cross-sectional, observational, associational study, we used baseline data from the UK Biobank cohort of participants aged 37–73 years from across the UK. Environmental exposure data were derived from a modelled and linked built environment database. Residential greenness was assessed with a 0·5 m resolution Normalised Difference Vegetation Index, which is derived from spectral reflectance measurements in remotely sensed colour infrared data and measured within geocoded dwelling catchments. Other environment metrics included street-level movement density, terrain, and fine particulate exposures. A series of logistic models examined associations between residential greenness and odds of major depressive disorder after adjusting for activity-influencing environments and individual covariates.

Findings Of 122 993 participants with data on major depressive disorder, the study analytical sample comprised 94 879 (77·1%) participants recruited across ten UK Biobank assessment centres between April 29, 2009, and Oct 1, 2010. A protective effect of greenness on depression was consistently observed, with 4·0% lower odds of major depressive disorder per interquartile increment in Normalised Difference Vegetation Index greenness (odds ratio 0·960, 95% CI 0·93–0·99; p=0·0044). Interaction analyses indicated that the beneficial effects of greenness were more pronounced among women, participants younger than 60 years, and participants residing in areas with low neighbourhood socioeconomic status or high urbanicity.

Interpretation The results point to the benefits of well designed green environments on mental health. Further longitudinal studies are needed to decipher causal pathways. In the UK, policies aimed at optimising allocation and design of green spaces might help preserve psychological ecosystem services, thereby, improving the mental wellbeing of populations and enhancing the mental capital of cities.

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Introduction

Given the present unprecedented rate of urbanisation, about 60% of the global population are predicted to reside in cities by 2030, with one in every three people living in cities with at least half a million inhabitants.[1] Typically, cities are characterised by highly dense, impervious, built-up spaces and a scarcity of natural environments, with the associated potential effects on mental health. Dynamic stress vulnerability models have reported links between reduced exposure to green environments and enhanced vulnerability to the negative health effects of stressful life events, which can result in increments in the proportion of the population with mental disorders and an overall reduction in the mental capital of cities.[2–4] In recent years, mental disorders, including mood disorders, have emerged as a leading cause of global disease burden. They also act as risk factors for the development of communicable and non-communicable diseases, and contribute to accidental and non-accidental injuries.[5–7] The UK's total annual expenditure on brain disorders was estimated to be approximately €134 billion in 2010, of which €19·24 billion was incurred on mood disorders, accounting for approximately 3·9 million annual cases or 8·73% of all brain disorders.[8]

The causes of mental health disorders are complex, with a long latency between exposures and subsequent incidence and progression. A systems-based life course approach towards enhancing the mental capital of cities and wellbeing of their populations has been proposed.[9]

Research in context

Evidence before this study

We searched online databases, including PubMed, MEDLINE, EBSCO, Scopus, and Google/Google Scholar databases, for studies and reports published in English between Jan 1, 1984, and Feb 10, 2018, using a combination of search terms, including "residential greenness", "green space", "NDVI", or "built environment", and "mental health", "depression", or "major depressive disorder".

Mental health disorders have emerged as a leading cause of the global burden of disease. At the same time, the present unprecedented pace of urbanisation and an increasing proportion of impervious built-up spaces in our cities have resulted in reduced exposures to salutogenic green environments. Several studies have examined the links between exposure to green environments and mental health, with most studies suggesting beneficial effects. Green exposure has been measured in terms of access to green spaces (proportion of green spaces within a residential neighbourhood) as well as the general salutogenic potential of green environments. The protective effects of residential green have been hypothesised to originate from one or more of its functional roles: as restorative stress-relieving spaces; supportive social interaction spaces promoting a sense of community; active living spaces facilitating physical activity; and natural filters ameliorating the adverse effects of negative exposures such as air, noise, and thermal pollution.

Notwithstanding the evidence generated so far, the links between residential green exposure and mental health still remain equivocal in adults. Many of the studies linking residential green exposure with mental health have used coarse measures of green exposure, whereas a few studies have used the Normalised Difference Vegetation Index as an index of salutogenic green, although of low-to-moderate spatial resolution. Most studies so far have been small scale and done in homogeneous environmental settings, resulting in limited statistical power and generalisability.

Added value of this study

The present study is the first of its kind to use the UK Biobank data to investigate links between green exposure and mental health. The study used a large and diverse analytical sample across ten UK cities of 94 879 middle-aged and older adults, a crucial life stage for the onset and progression of incipient mental disorders. A large spatially diverse sample also enabled sufficient statistical power for the examination of interactions. The study used structured and validated diagnostic criteria to assess lifetime probable major depressive disorders and was able to comprehensively adjust for sources of confounding. To our knowledge, this is the first mental health-related study to use a very high-resolution metric of residential greenness (0·5 m resolution index of salutogenic green derived from colour infrared imageries) that is adjusted for other objectively measured physical environment exposures, which are all measured within functional catchments of participants' dwellings.

The study consistently found a protective association between greenness and lifetime depression status, reporting a 4% lower odds of major depressive disorder with every interquartile increment in residential greenness after adjusting for all other factors. The beneficial effects of greenness were more pronounced among women, participants younger than 60 years, and participants residing in areas with low neighbourhood socioeconomic status or high urbanicity.

Implications of all the available evidence

The results of our study point to the protective effects of well designed green environments on mental health. These findings have notable policy implications with respect to optimising allocation and design of green spaces to preserve psychological ecosystem services and thereby improve the mental wellbeing of a population and enhance the mental capital of cities.

The importance of such a holistic approach has been emphasised by the inclusion of mental health within the Sustainable Development Goals.[10,11] Relatedly, exposure to residential green environment has also been regarded as an effective upstream-level urban intervention with an aim to reduce the public health burden of mental disorders.[12]

Some studies report a beneficial effect of contact with green environments on health, in general,[13–15] and more specifically, with regard to stress, mood, and mental health.[16,17] Several studies have established a protective independent association between various indicators of mental health and the percentage of green space within a residential neighbourhood,[18–21] the amount of tree cover in an urban area,[22] and the overall exposure of individuals to salutogenic green environments.[23–25] These protective effects of residential green spaces have been explained in terms of four mechanisms related to their specific functional roles: restorative, stress-relieving spaces;[4,26–28] supportive, social interaction spaces that promote a sense of community;[29] active living spaces that facilitate physical activity;[30–32] and natural filters that ameliorate the adverse effects of air, noise, and thermal pollution.[33–35]

Despite the substantial body of evidence, the links between residential green exposure and mental health still remain far from conclusive in adults.[17] Many of the studies have used coarse measures of green exposure, expressed as a proportion of greenness based on land cover maps within a specific catchment or census geography, thereby neglecting to include private gardens, street trees, and green spaces that do not meet a specific criterion, such as a size threshold, and hindering the study's replicability and comparability. A few studies have used the Normalised Difference Vegetation Index (NDVI), an index of greenery derived from Landsat satellite data, as an overall measure

of green exposure (although at a low-to-moderate resolution). Most studies so far have been small scale and done in homogeneous environmental settings, resulting in limited statistical power and generalisability. Furthermore, most studies do not adjust for other aspects of activity-influencing built environment and individual-level confounding effects, or consider interaction effects.

The present study analyses a UK-wide population health dataset of unprecedented size and diversity for greenspace mental health research. It uses highly characterised metrics of green exposure to investigate cross-sectional associations between residential greenness and major depressive disorders, after adjusting for pertinent built environment (ie, walkability, terrain, and air pollution) and individual confounders. Because exposure to greenness and its relation to health is often stratified by underlying factors such as socioeconomic status and urbanicity,[18,36,37] this study also did analyses stratified by age, sex, neighbourhood socioeconomic status, and urbanicity, and analysed their interactions.

Methods

Analytical sample

This cross-sectional, observational, associational study analysed the UK Biobank baseline data on health and environment exposures. The National Health Service Register randomly sent out around 9·2 million invitation letters to potential participants who resided within a 25 mile radius of a UK Biobank collection centre, each of which are located in 22 cities across the UK. 502 649 adult participants aged 37–73 years were eventually recruited in the UK Biobank study, achieving a response rate of 5·5%.[38,39] The participants provided electronically signed consent. The range and scale of the UK Biobank study enables accumulation of an adequate number of cases of particular diseases within a reasonable follow-up period for clinically reliable effect detection. The baseline examination collected a wide range of information, including information on sociodemographics, lifestyle, and medical history through a series of touch-screen questionnaires; anthropometric measurements; biological sampling (blood, urine, and saliva); and imaging, and involved linkage with hospital-related outcomes. Individual-level, health-influencing, environment exposures were modelled within functional neighbourhoods for each participant.

The mental health component of the UK Biobank was an enhancement to the baseline data collection, and questions on depressive symptoms were added to the assessment protocol during the last 2 years of recruitment. These psychological inventories were available to participants who visited the remaining ten collection centres in the last 2 years of the baseline phase and fulfilled the diagnostic criteria of mood disorder.[38] The analytical sample excluded participants who subsequently dropped out or who did not meet the diagnostic criteria for a mood disorder. We also excluded from the analyses participants with missing data on residential green exposure and other individual confounders. The participants of our analytical sample attended the assessment centres between April 29, 2009, and Oct 1, 2010.

UK Biobank received ethical approvals from the North West Multi-centre Research Ethics Committee, the Community Health Index Advisory Group, the Patient Information Advisory Group, and the National Health Service National Research Ethics Service. The detailed cohort protocol, scientific rationale, and study design are described elsewhere.

For the **cohort protocol, scientific rationale, and study design** [redacted]

Measurement of major depressive disorder

Depression was defined as per UK Biobank's assessment protocol for lifetime experience of probable major depressive disorder. The classification and definition of lifetime history of mood disorders in UK Biobank was based on structured and validated diagnostic criteria reported previously.[40,41] Briefly, the assessment of major depressive disorder comprised items relating to lifetime experience of minor or major depression, items from the Patient Health Questionnaire, and items related to social support for mental health.[40,42] As such, the binary outcome variable comprised participants with no lifetime experience of major depressive disorder (0 or "no case") and participants who had experienced a major depressive disorder (1 or "case"). The criteria for participants who had experienced a major depressive disorder included those who had experienced a single probable lifetime episode of major depression, probable recurrent major depression (moderate), or probable recurrent major depression (severe), or any combination thereof (panel).

Measurement of residential environment exposures

Residential environment exposure data were derived from the UK Biobank Urban Morphometric Platform (UKBUMP). UKBUMP is a high-resolution spatial database of health-influencing environment exposures modelled within multiscale residential neighbourhoods of each UK Biobank participant's geocoded dwelling. Environmental exposure metrics were developed through spatial and network analyses of data from multiple UK-wide spatial databases, resulting in multiple exposure variables related to greenness, urban density, destination accessibility, street-level accessibility, terrain, and deprivation.[43,44] Briefly, UKBUMP was developed by geocoding participants' dwelling addresses to the level of building footprints, delineating multiscale dwelling neighbourhoods by defining street network buffers centred on the geocoded dwelling locations in ArcGIS12 Network Analyst, and measuring environmental exposures within these functional neighbourhoods. After linking the exposure metrics to the participants' dwelling locations, the data were reanonymised. Accurate data on building-level land uses and street networks were sourced from UK Ordnance Survey AddressBase Premium and MasterMap Integrated Transport Network databases, whereas residential greenness was modelled from high-resolution (50×50 cm²)

Panel: **UK Biobank study's diagnostic criteria for classification of lifetime experience of probable major depressive disorders**[40,41]

Single probable episode of major depressive disorder
Ever depressed or down for a whole week; plus at least 2 weeks' duration; plus only one episode; plus ever seen a general practitioner or a psychiatrist for "nerves, anxiety, depression" OR ever anhedonic (unenthusiasm or uninterest) for a whole week; plus at least 2 weeks' duration; plus only one episode; plus ever seen a general practitioner or a psychiatrist for "nerves, anxiety, depression"

Probable recurrent major depressive disorder (moderate)
Ever depressed or down for a whole week; plus at least 2 weeks' duration; plus at least two episodes; plus ever seen a general practitioner (but not a psychiatrist) for "nerves, anxiety, depression" OR ever anhedonic (unenthusiasm or uninterest) for a whole week; plus at least 2 weeks' duration; plus at least two episodes; plus ever seen a general practitioner (but not a psychiatrist) for "nerves, anxiety, depression"

Probable recurrent major depressive disorder (severe)
Ever depressed or down for a whole week; plus at least 2 weeks' duration; plus at least two episodes; plus ever seen a psychiatrist for "nerves, anxiety, depression" OR ever anhedonic (unenthusiasm or uninterest) for a whole week; plus at least 2 weeks' duration; plus at least two episodes; plus ever seen a psychiatrist for "nerves, anxiety, depression"

colour infrared data captured during aerial photography with the Vexcel UltraCamD and the Leica ADS4.[43]

Residential greenness

Residential exposure to salutogenic green environment was measured in terms of mean NDVI within a 500 m catchment radius of geocoded UK Biobank participants' dwellings. NDVI is a unit-less index of relative overall vegetation density and quality, and is derived from differential surface reflectance in the red and near infrared regions,[45] which is measured with a remote sensing device. Chlorophyll in healthy vegetation absorbs radiation in the visible red region (630–690 nm) of the electromagnetic spectrum and reflects radiation in the near-infrared region (760–900 nm). This differential in the absorbance and reflectance of wavelengths by chlorophyll is used as a proxy for green quality and intensity. The differential is measured using the following formula:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})}$$

The formula includes the spectral reflectance measurements acquired in the visible (RED) and near-infrared regions (NIR) of the electromagnetic spectrum. Index scores range between –1 and 1, with higher values indicating higher densities of green vegetation.

In the present study, NDVI greenness was derived from a series of 0·5 m resolution, colour-infrared imagery collected by Bluesky (Ashby-De-La-Zouch, UK) with the help of specially developed sensors mounted underneath a survey aircraft. Summer-time images of the study areas collected over similar temporal scales (across the baseline phase of the UK Biobank study) were stitched together to avoid temporal mismatch. After excluding large water bodies, we modelled mean NDVI within a 500 m residential buffer of each UK Biobank participant. Selection of a 500 m catchment area for measuring residential green exposures was based on our previous studies[46,47] and on other previous reports[48,49] that used a quarter mile (400–500 m) neighbourhood for measuring NDVI greenness.

Physical environment

Among the physical environment exposures, terrain was modelled in ArcGIS12 Spatial Analyst from a 5 m resolution Bluesky digital terrain model and expressed as variability (SD) of slope, in degrees, within a 0·5 km residential catchment of UK Biobank participants' dwellings. As such, the metric is able to differentiate between flat and hilly surface within the residential catchment.

Exposure to $PM_{2.5}$ obtained from UK Biobank's linked air pollution exposure data was used as a proxy for traffic-related air pollution. The measurement was based on monitoring on three occasions over a 14 day period during the cold, warm, and intermediate seasons of the year. Individual annual exposure to particulate matter concentrations around geocoded residential addresses was derived from land-use regression models.[50]

Built environment

Built-environment metrics from UKBUMP were assessed within a 1 km street catchment of participants' dwellings. Street-level movement density was modelled in terms of through-movement potential of the street segments, also termed as betweenness centrality in graph theoretic terminology. The method has been used in active living research and described elsewhere.[51,52] The UK-wide street network data for the study area comprised approximately 4 million street segments, which were extracted from the OS MasterMap Integrated Transport Network database, transcribed into an access graph model, and subjected to network analysis in sDNA[53] to model street-level movement density. Movement density is expressed as the simulated counts of movement through each link in the network, given its relative position and topological connectivity with other segments within the network. The measure also acts as a proxy for relative accessibility and centrality of a place. Betweenness centrality of x in a graph of N links might be defined as:

$$BtWl(x) = \sum_{y \varepsilon N} \sum_{z \varepsilon R_y} L(y)\, L(z)\, P(z) \mathrm{OD}(y,z,x)$$

In the formula, y and z are the geodesic endpoints; R_y is the set of links within a defined neighbourhood catchment from y; $L(y)$ is the length of link y and $L(z)$ is the length of link z; and $P(z)$ is the proportion of link z within the defined radius.

The origin-destination function (OD) is defined as:

$$\mathrm{OD} = \begin{cases} 1, \text{ if } x \text{ is on the geodesics from } y \text{ to } z \\ \frac{1}{2}, \text{ if } x \equiv y \not\equiv z \\ \frac{1}{2}, \text{ if } x \equiv z \not\equiv y \\ \frac{1}{2}, \text{ if } x \equiv z \equiv y \\ 0, \text{ otherwise} \end{cases}$$

An objective index of urbanicity within a 1 km residential catchment was developed from the UKBUMP built-environment variables to investigate associations between residential greenness and major depressive disorder, stratified by urbanicity quartiles. Urbanicity was defined as:

$$\mathrm{Urbanicity} = zscore_{resid} + zscore_{retail} + zscore_{PT} + zscore_{street\ movement}$$

The formula includes the density of residential housing (*resid*), retail (*retail*), and public transport (*PT*) in units per km² street catchment, in addition to street-level movement density (*street movement*).

Individual-level covariates

On the basis of previous scientific literature, the study adjusted for demographic covariates (age, sex, highest educational qualification, and employment status), smoking status, and prevalent comorbidities (body-mass index [BMI] status, doctor-diagnosed cardiometabolic disease, and diabetes).

Socioeconomic status was assessed at household and neighbourhood levels in terms of mean annual household income before tax and Townsend deprivation index scores,[54] which is a composite index of four postcode-level socioeconomic status variables (household overcrowding, unemployment, non-home ownership, and non-car ownership), with a higher score indicative of lower neighbourhood socioeconomic status.

We used participation in leisure and social activities as a proxy for social interaction and support. Level of participation was based on response to the questionnaire: "Which of the following do you attend once a week or more often? (You can select more than one)"; with available responses being none; pub or social club; religious group; sports club or gym; and adult education class or other group activity. Responses were converted into a six-factor variable: none, pub or social club, religious group, sports club or gym, adult education class and other, and combination of two or more activities.

Statistical analyses

The prevalence of lifetime experience of probable major depressive disorder was modelled as a two factor variable (case or non-case) as per UK Biobank's assessment protocol. Age was coded as a three-factor variable (38–50 years, 51–60 years, or 61–73 years) and sex as a two-factor variable (female or male). Highest educational attainment was defined as a five-factor variable (none; O levels, GCSEs, or CSEs; A levels or AS levels; NVQ, HND, HNC, or other professional qualification; or college or university degree) and employment as a three-factor variable (employed; retired; or unemployed, home maker, or other). Mean annual household income before tax was expressed as a four-factor variable (<£18 000, £18 000–£30 999, £31 000–£51 999, or ≥£52 000). The household income data were available for 82 839 participants in the analytical sample. Townsend scores were categorised into quintiles and used as a five-factor variable. Smoking status was coded as non-smoker, previous smoker, and current smoker. Doctor-diagnosed cardiometabolic disease was transformed into a four-factor variable (none; high blood pressure; heart attack, angina, or stroke; or both high blood pressure and heart attack, angina, or stroke) and diabetes was coded as a two-factor variables (yes or no). Measured BMI status was expressed as a three-factor variable (<25 kg/m²; ≥25 kg/m² and <30 kg/m²; or ≥30 kg/m²). Terrain variability and walkability (expressed as movement density) were transformed into quartiles.

The study followed a multi-layered analyses strategy. Logistic regression models investigated the association between residential greenness and odds of major depressive disorder. Odds ratios (OR) and two-tailed 95% CIs estimated by bootstrapping have been presented for each IQR increment in NDVI. In model 1, we modelled initial crude estimates adjusted for age. Model 2 further adjusted for sex, educational qualification, employment status, smoking status, prevalent obesity, cardiometabolic disease, and diabetes status; model 3 additionally adjusted for physical and built environment variables of terrain, exposure to fine particulates, and activity-influencing movement density; and model 4 additionally adjusted for household and neighbourhood socioeconomic status and leisure and social activity. Multicollinearity among predictor variables was assessed through Pearson's correlation coefficients and variance inflation factors to ensure parsimonious fit.

Stratified analyses were done by age, sex, urbanicity, and neighbourhood socioeconomic status to investigate potential changes in point estimates and level of significance across each stratum. As a further step, the study analysed the interaction effects of age and urbanicity, sex and urbanicity, age and neighbourhood socioeconomic status, and sex and neighbourhood socioeconomic status on the relation between residential greenness and prevalence of major depressive disorder.

All analyses were done in statistical software Stata 14.

	Depression status		Analytical sample (n=94 879)
	No major depressive disorders (n=70 531)	Major depressive disorders (n=24 348)	
Age (years)	57·38 (8·1)	55·73 (8·0)	56·96 (8·1)
Residential greenness	0·213 (0·1)	0·209 (0·1)	0·211 (0·1)
Socioeconomic status (Townsend index)	−1·44 (2·8)	−1·16 (2·9)	−1·37 (2·8)
Sex			
Female	35 409 (50·2%)	15 854 (65·1%)	51 263 (54·0%)
Male	35 122 (49·8%)	8494 (34·9%)	43 616 (46·0%)
Highest educational qualification			
None	10 918 (15·5%)	2975 (12·2%)	13 893 (14·6%)
College or university degree	23 912 (33·9%)	8833 (36·3%)	32 745 (34·5%)
O levels, GCSEs, or CSEs	19 126 (27·1%)	6739 (27·7%)	25 865 (27·3%)
A levels or AS levels	7991 (11·3%)	3015 (12·4%)	11 006 (11·6%)
NVQ, HND, HNC, or other professional	8584 (12·2%)	2786 (11·4%)	11 370 (12·0%)
Employment status			
Employed	39 519 (56·0%)	13 927 (57·2%)	53 446 (56·3%)
Retired	26 079 (37·0%)	7710 (31·7%)	33 789 (35·6%)
Unemployed, home maker, or other	4933 (7·0%)	2711 (11·1%)	7644 (8·1%)
Household income*			
<£18 000	11 693 (19·2%)	5269 (23·9%)	16 962 (20·5%)
£18 000–£30 999	15 375 (25·3%)	5522 (25·1%)	20 897 (25·2%)
£31 000–£51 999	15 984 (26·3%)	5759 (26·1%)	21 743 (26·2%)
≥£52 000	17 764 (29·2%)	5473 (24·9%)	23 237 (28·1%)
Smoking status			
Non-smoker	40 709 (57·7%)	12 292 (50·5%)	53 001 (55·9%)
Previous smoker	24 035 (34·1%)	9034 (37·1%)	33 069 (34·9%)
Current smoker	5787 (8·2%)	3022 (12·4%)	8809 (9·3%)
Leisure or social activities			
None	21 133 (30·0%)	7674 (31·5%)	28 807 (30·4%)
Pub or social club	9010 (12·8%)	2645 (10·9%)	11 655 (12·3%)
Religious group	4581 (6·5%)	1415 (5·8%)	5996 (6·3%)
Sports club or gym	10 108 (14·3%)	3088 (12·7%)	13 196 (13·9%)
Adult education or others	7682 (10·9%)	3019 (12·4%)	10 701 (11·3%)
Two or more of above activities	18 017 (25·5%)	6507 (26·7%)	24 524 (25·8%)
Body-mass index status			
Normal weight	24 046 (34·1%)	7906 (32·5%)	31 952 (33·7%)
Overweight	30 334 (43%)	9834 (40·4%)	40 168 (42·3%)
Obese	16 151 (22·9%)	6608 (27·1%)	22 759 (24·0%)
Vascular problems			
None	49 902 (70·8%)	16 946 (69·6%)	66 848 (70·5%)
High blood pressure	16 931 (24%)	5973 (24·5%)	22 904 (24·1%)
Heart attack, angina, or stroke	1826 (2·6%)	615 (2·5%)	2441 (2·6%)
High blood pressure and heart attack, angina, or stroke	1872 (2·7%)	814 (3·3%)	2686 (2·8%)
Diabetes			
None	66 779 (94·7%)	22 981 (94·4%)	89 760 (94·6%)
Yes	3752 (5·3%)	1367 (5·6%)	5119 (5·4%)

Data are mean (SD) or n (%). *Data on household income were available for 82 839 participants of the analytical sample (60 816 in the no major depressive disorder category and 22 023 in the major depressive disorders category).

Table 1: **Characteristics of UK Biobank analytical sample**

Role of the funding source

The funders and UK Biobank participants did not participate in developing the research questions, outcome measures, and environmental measures of the present study. They had no role in study design, modelling, data collection, data analysis, data interpretation, or writing of the report. CS, CW, and JG had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

172 751 participants visited the remaining ten UK Biobank collection centres in the last 2 years of the baseline phase and completed the mental health component of the UK Biobank assessment protocol. After excluding participants who subsequently dropped out and participants who did not meet the diagnostic criteria for a mood disorder, valid data were available for 122 993 participants. After excluding missing data on residential green exposure for 23 945 (19·5%) participants and other individual confounders for 4169 (3·4%) participants, an analytical sample of 94 879 (77·1%) participants was available for analyses.

The analytical sample remained representative of the full UK Biobank cohort (table 1; appendix). Overall, 24 348 (25·7%) patients in the sample had major depressive disorders. In all our models, the Pearson's correlation coefficients remained less than 0·23 and the variance inflation factors remained less than 1·08, indicating low levels of collinearity.

Exposure to residential greenness remained significantly associated with major depressive disorder, with 4·0–4·9% lower odds of major depressive disorder reported across models 1–4 (table 2). Adjusting for individual-level covariates, physical and built environment variables (model 3), an interquartile increment in NDVI greenness within a 500 m catchment was associated with 4·3% lower odds of major depressive disorder (OR 0·957, 95% CI 0·93–0·98; p=0·0008; table 2; see appendix for full table). After further adjustments for socioeconomic status and social activities (in the fully adjusted model 4), an interquartile increment in NDVI was associated with 4·0% lower odds of major depressive disorder (OR 0·960, 0·93–0·99; p=0·0044; table 2).

Among the other significant environment exposure variables in our fully adjusted model 4, terrain variability (ie, more hilly terrain) was associated with higher odds of major depressive disorder, with the third (p=0·026) and fourth (p<0·0001) quartiles of terrain variability having higher odds of major depressive disorder than the first quartile. Street-level movement density, measured as betweenness centrality, was associated with lower odds of major depressive disorder, with the second (p=0·013) and third (p=0·0030) quartiles (ie, areas of greater street-level movement density) having lower odds of major depressive disorder than the first quartile. Higher mean annual household income was consistently associated with lower odds of major depressive disorder (p<0·0001 for those

earning £18 000–£30 999, p<0·0001 for those earning £31 000–£51 999, and p<0·0001 for those earning ≥£52 000, in reference to the lower income group earning <£18 000). Lower neighbourhood socioeconomic status (expressed in terms of Townsend's deprivation score) was associated with higher odds of major depressive disorder, with the results being significant for the fifth quintile only (p=0·048 in reference to the first quintile). In reference to participants not engaged in any social activities, participants attending pubs or participating in social club-based activities (p<0·0001), engaging in religious group activities (p<0·0001), and attending a sports club or gym (p<0·0001) reported significantly lower odds of major depressive disorder.

Rerunning the analysis with the residential greenness as a factor variable categorised into quartiles indicated a beneficial effect for the third (OR 0·933, 95% CI 0·89–0·98; p=0·0029) and fourth (OR 0·947, 0·90–0·99; p=0·023) quartiles but not the second quartile (OR 1·039, 0·99–1·09; p=0·090) in reference to the first quartile and subsequent to all adjustments.

In the stratified models (figure 1), the association between residential greenness and odds of major depressive disorder remained significant only in female participants (OR 0·96, 95% CI 0·92–0·99; p=0·022); participants younger than 60 years (OR 0·96, 0·92–0·99; p=0·017); participants in the third (OR 0·92, 0·87–0·98; p=0·0085) and fourth (OR 0·91, 0·85–0·97; p=0·0070) urbanicity quartiles; and participants in the lower neighbourhood socioeconomic status quintiles, namely the fourth (OR 0·89, 0·83–0·96; p=0·0037) and fifth (0·85, 0·78–0·93; p=0·0003) quintiles of the Townsend index.

Consistent with the results of the stratified analyses, interactions between age and urbanicity and between sex and urbanicity found a slightly stronger protective association of residential greenness on major depressive disorder for women and participants younger than 60 years, with the effects being significant only in urban areas (ie, the third and fourth urbanicity quartiles; figure 2). Similarly, interaction models of age and neighbourhood socioeconomic status and of sex and neighbourhood socioeconomic status reported slightly stronger protective effects in women and participants younger than 60 years, with the effects being significant among lower neighbourhood socioeconomic status groups (ie, the fourth and fifth quintiles of the Townsend index; figure 2).

	Model 3, OR (95% CI)	Model 4, OR (95% CI)
Residential greenness (500 m:NDVI)*	0·957 (0·93–0·98)	0·960 (0·93–0·99)
Physical environment		
Terrain variabiliy†		
Low (Q1)	1 (ref)	1 (ref)
Low–medium (Q2)	1·035 (0·99–1·08)	1·017 (0·97–1·06)
High–medium (Q3)	1·050 (1·01–1·09)	1·052 (1·01–1·10)
High (Q4)	1·133 (1·09–1·18)	1·104 (1·06–1·16)
$PM_{2·5}$ (per 1 μg/m³)	1·024 (1·01–1·04)	0·996 (0·98–1·02)
Built environment (street-level movement density)†		
Low (Q1)	1 (ref)	1 (ref)
Low–medium (Q2)	0·930 (0·89–0·97)	0·942 (0·90–0·99)
High–medium (Q3)	0·908 (0·87–0·95)	0·934 (0·89–0·98)
High (Q4)	0·938 (0·90–0·98)	0·955 (0·91–1·00)
Socioeconomic status and social environment		
Individual socioeconomic status (household income)‡		
<£18 000	NA	1 (ref)
£18 000–£30 999	NA	0·800 (0·76–0·84)
£31 000–£51 999	NA	0·743 (0·71–0·78)
≥£52 000	NA	0·595 (0·56–0·63)
Neighbourhood socioeconomic status (Townsend index)§		
Low (Qn1)	NA	1 (ref)
Qn2	NA	1·025 (0·98–1·08)
Medium (Qn3)	NA	1·042 (0·99–1·10)
Qn4	NA	1·019 (0·97–1·07)
High (Qn5)	NA	1·057 (1·00–1·12)
Activities		
None	NA	1 (ref)
Pub or social club	NA	0·889 (0·84–0·94)
Religious group	NA	0·847 (0·79–0·91)
Sports club or gym	NA	0·894 (0·85–0·94)
Adult education class or other	NA	1·076 (1·02–1·14)
Two or more activities	NA	1·025 (0·98–1·07)

Analysis includes data for 94 879 UK Biobank participants. Model 3 is adjusted for age, individual-level covariates, and physical environment (terrain, street-level movement density, and exposure to $PM_{2·5}$). Model 4 is a fully adjusted model, additionally adjusting for household income, neighbourhood-level socioeconomic status, and social activities for 82 839 participants. OR=odds ratio. NDVI=Normalised Difference Vegetation Index. NA=not applicable. *The OR for residential greenness was 0·954 (95% CI 0·93–0·98) for model 1, which is adjusted for age, and 0·951 (0·93–0·98) for model 2, which is adjusted for age and individual-level covariates (sex, highest educational qualification, employment, smoking status, body-mass index status, doctor-diagnosed cerebrovascular disease, and diabetes status). †Q1, Q2, Q3, and Q4 represent the first, second, third, and fourth quartiles, respectively. ‡Data on household income were available for 82 839 participants of the analytical sample. §Qn1, Qn2, Qn3, Qn4, and Qn5 represent first, second, third, fourth, and fifth quintiles, respectively.

Table 2: **Association between residential greenness and odds of major depressive disorders**

Discussion

In this large, UK-wide, cross-sectional study, residential greenness was consistently associated with lower odds of depression, with the results remaining robust to adjustments for other physical, built, and social environment variables. This is one of the largest studies to use very high-resolution metrics of residential greenness (0·5 m on the ground measured from an aircraft) and to have adjusted for other objectively measured physical environment exposures.

See **Online** for appendix

This study reported a protective association of greenness on lifetime depression status, with effect sizes being moderate at 4% lower odds of major depressive disorder with every interquartile increment in residential greenness after adjusting for all other factors. This finding lends support to previous studies reporting protective effects of residential green exposure on depression.[18–21,23,24] One large-scale study[19] has reported that having 10% more greenness than average within 1 km

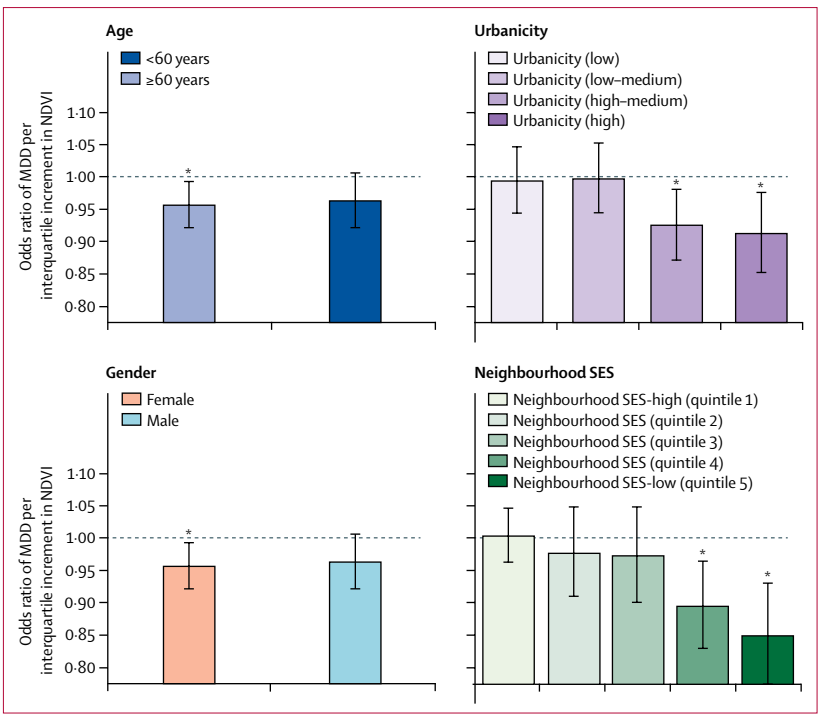


Figure 1: **Association between residential greenness and odds of major depressive disorders stratified by age, gender, urbanicity, and neighbourhood socioeconomic status**

Each model is adjusted for age, sex, highest educational qualification, employment status, social activities, household income, neighbourhood socioeconomic status, body-mass index status, cardiometabolic disease, diabetes, terrain, street-movement density, and $PM_{2.5}$. Urbanicity was measured as an aggregated index of residential, retail, public transport, and street-movement density, and expressed in quartiles. Neighbourhood socioeconomic status was defined in terms of Townsend's index of deprivation and expressed as quintiles, with higher quintiles indicating higher levels of deprivation. MDD=major depressive disorder. NDVI=Normalised Difference Vegetation Index. SES=socioeconomic status. *p<0·05.

was associated with 4% lower odds of depression, and within 3 km was associated with 2% lower odds of depression. A US study[23] involving 2479 residents of Wisconsin reported that a 25% increment in NDVI greenness was associated with a 1·4 unit reduction in a depression anxiety and stress scale. Another study[24] of 8793 participants in Catalonia, Spain, reported that each interquartile increment in NDVI greenness was associated with a 21% lower perceived risk of poor mental health and a 19% lower risk of perceived depression or anxiety. In both the later studies,[23,24] NDVI greenness was derived from 30 m resolution Landsat satellite data and our study improves on these findings in terms of both spatial accuracy and confounders.

Green spaces and wellbeing are intrinsically linked.[55] The observed overall protective effects of residential green on depression status might be interpreted in terms of mechanisms oriented around biology, physiology, and lifestyle. The biophilia hypothesis suggests that biologically, human beings have an innate affinity towards natural environments, life forms, and life-like processes as a consequence of evolution and natural selection, and such environments are inherently associated with lower stress levels than more urban environments.[15,56] According to the stress reduction hypothesis, residential green can provide restorative stress-relieving environments that are capable of instilling a positive psychological state.[26–28,57] Green environments might also provide stimuli for attention restoration and associated cognitive benefits.[58,59] At a physiological level, evidence has been established for beneficial, stress-relieving effects of green exposure in urban settings, assessed through biological markers, including salivary cortisol,[60] amylase,[61] telomere length,[62] and improved cardiometabolic health.[63] At a neurobiological level, rumination and associated neural activity in the subgenual prefrontal cortex have been linked to elevated levels of depression and psychological disorders.[64] The place-cells within the hippocampus also help encode attributes of real-world places, enabling the formation of cognitive maps of places, which again affects an individual's sense of attachment and route choice.[65] A 2015 study[66] reported that a 90 min walk in a green environment decreases both self-reported rumination and subgenual prefrontal cortex activity, whereas the same duration of walk in an urban setting had no effect. Rumination is a maladaptive attentional focus and has been linked to onset of depressive episodes and mental disorders. Neurological evidence has shown that the subgenual prefrontal cortex in the brain is particularly active during rumination. At a lifestyle level, residential greenness provides spaces for people to interact and support one another and facilitates a positive perception of neighbourhood and sense of community.[29,67] Furthermore, green spaces act as activity spaces, facilitating participation in physical and social activities.[31,68] The protective effects[69] of physical activity on depression can plausibly be attributed to elevated levels of brain neurotransmitters, such as monoamines and endorphins, and to enhanced self-esteem.[70]

Unlike previous reports, our study also adjusted for activity-influencing environment metrics. As per previous findings,[71] terrain variability was associated with higher odds of major depressive disorder. Terrain variability acts as a proxy for the degree of impediments to physical mobility, with its negative association with major depressive disorder possibly attributable to the effects of reduced functional capacity among participants residing in variable terrain. Furthermore, in a varied terrain, people might not be able to make as much use of available green spaces. Built environment metrics of density and form capture variations in the configuration of urban spaces in a city and these might directly affect mental health independently of green effects. In addition to green exposure, an optimised neighbourhood design might act as buffers against stressful environments. A 2018 study[72] reported more pronounced beneficial effects of walkability on hypertension in the high-green quartiles than in the low-green quartiles. Built-environment design and configuration determines accessibility to green spaces and, as such, actual usage

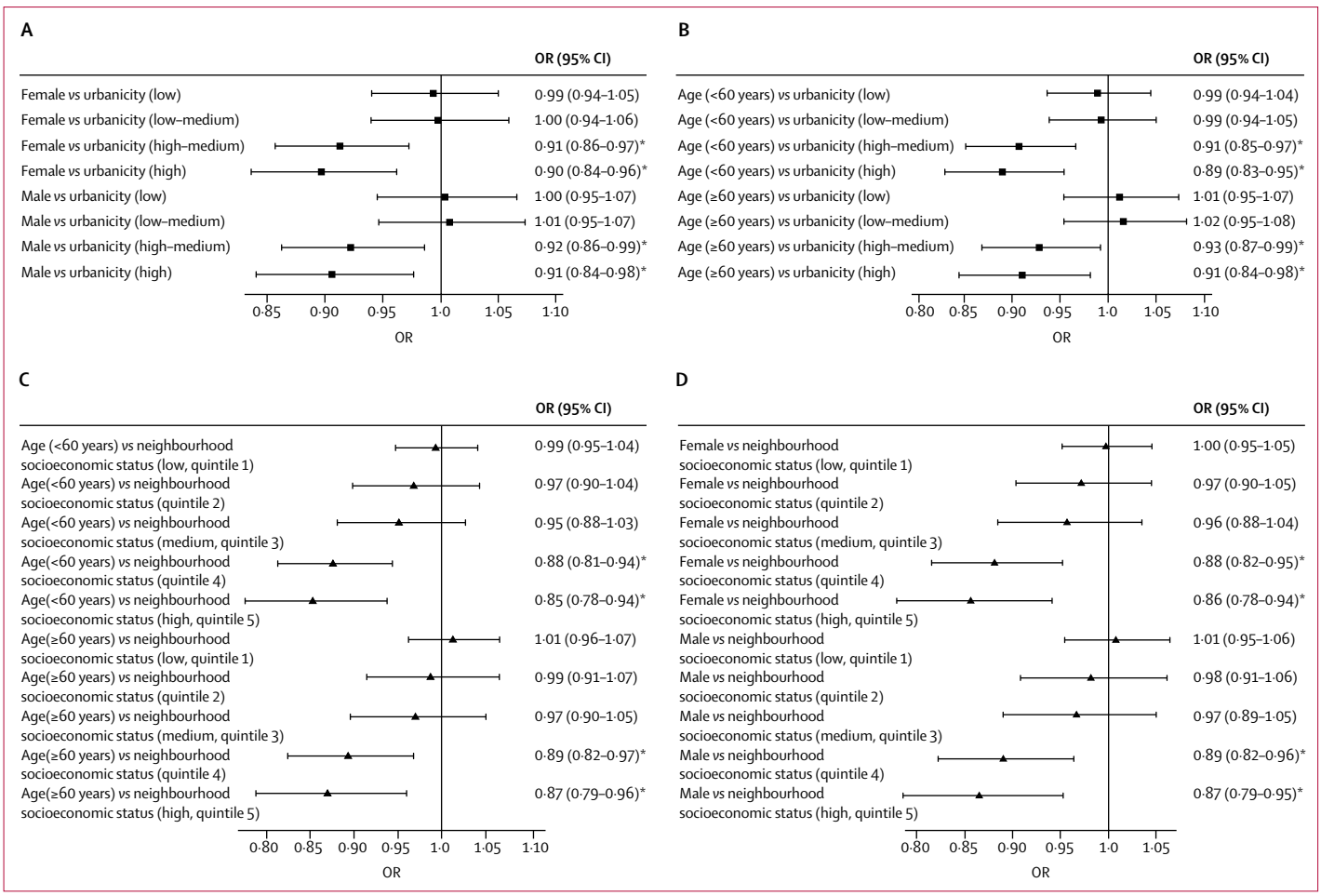


Figure 2: **Models of interaction effects in the association between residential greenness and odds of major depressive disorder**
Each model is adjusted for age, sex, highest educational qualification, employment status, social activities, household income, neighbourhood socioeconomic status, body-mass index status, cardiometabolic disease, diabetes, terrain, street-movement density, and $PM_{2·5}$. Urbanicity was measured as an aggregated index of residential, retail, public transport, and street-movement density, and expressed in quartiles. Neighbourhood socioeconomic status was defined in terms of Townsend's index of deprivation and expressed as quintiles, with higher quintiles indicating higher levels of deprivation. OR=odds ratio. *p<0·01.

and levels of physical activity. In the present study, street-level movement density, captured by the index of betweenness centrality, was consistently associated with reduced odds of major depressive disorder. This finding points to the protective effects of well designed and connected neighbourhoods and greater activity and walking,[46] and hence, improved mental health.[71] Furthermore, a walkable, well designed community is associated with increased neighbourhood cohesion and social support. The beneficial effects of participation in leisure and social activities on major depressive disorder might point to the community social capital-based mechanism.[73] Corroborating previous studies,[18,37] this study reported that higher socioeconomic deprivation, measured by Townsend's score, was associated with higher odds of major depressive disorder.

In the subgroup analyses, the significant beneficial effects of residential green on major depressive disorders in women is attributable to increased daily exposure to functional neighbourhood environment and corresponds with previous findings.[18,24,74] The reduced effects in participants aged older than 60 years might be related to the reduced functional capacity in these population clusters.[75] The significantly higher protective effects of residential greenness reported in low neighbourhood socioeconomic status and high urbanicity groups than reported in their opposite counterparts has been reported previously.[18,37,76] The pronounced protective effects reported in the deprived and high urbanicity areas might originate from the restorative potential of green environments in exposure subgroups, which are generally associated with increased levels of stress.[77] Furthermore, in this study, urbanicity is a composite index of density, which is synonymous with compactness. The protective effects of green allocated in these areas stem from an increased density of exposed population, an increased degree of accessibility, and potentially increased usage.

The results of this study have important implications for public health and urban policies. Of specific interest is the use of green exposures as an upstream-level intervention to manage and minimise the burden of mental health disorders. Our findings will support public health and urban planning professionals in arguing for optimisation of residential green space exposure and related built environment attributes, in terms of allocation (size and shape), quality, density, and accessibility, with an aim to improve psychological ecosystem services[78] to yield benefits for individuals' mental health. Our findings also give guidance for more targeted interventions; in addition to urban environmental stressors, the characteristics of the resident population, especially their intrinsic sociodemographic and vulnerability profiles, need to be considered.

The study has several strengths. It used a high-quality, UK Biobank cohort dataset of unprecedented size and with substantial population-level and spatial diversity. Such a large analytical sample also meant the study had sufficient statistical power to investigate interactions. The study used clinically meaningful and validated instruments to define lifetime prevalence of major depressive disorders.[40] It also used highly characterised metrics of residential greenness and physical and built environment that were measured within neighbourhoods of an individual's dwelling. The NDVI has been previously validated as a measure of greenness in epidemiological research.[79] In the present study, it acted as an objective measure of green exposure (both density and quality) and as a proxy for capturing the intangible salutogenic potential within a residential environment. The use of very high resolution (50×50 cm²) colour infrared data captured during aerial photography with the Vexcel UltraCamD and the Leica ADS4 enabled extreme precision in green measurements. Previous studies have used conventional satellite remote-sensing data, for which the quality is often limited by low resolution, cloud cover, and atmospheric distortions.[46] In view of the established links between active living and depression,[69] the study also adjusted for other influencing environment features, which it operationalised through objective measures of terrain variability, street-level walkability, and exposure to fine particulate matter, in addition to adjusting for socioeconomic status, social activities, and other individual-level confounders.

This study also has some limitations. A cross-sectional study design limits confidence in the establishment of causal associations. Depressed participants might have migrated to greener areas and the resulting self-selection could potentially lead to underestimation of the effects of greenness on major depressive disorder. The study did not have data on the spatial mobility of participants over the baseline phase (2006–10) or on changes in exposures owing to migration from one address to another. Nonetheless, the mean duration of residence across the non-major depressive disorder and major depressive disorder groups was similar at 18 years and 16 years, respectively, and the introduction of duration of residence in the fully adjusted model did not produce any material effects on the point estimates and level of significance. As repeat-assessment data from the UK Biobank subsample become available, future studies should investigate the longitudinal associations of green exposure with major depressive disorder. The major depressive disorder outcome, being derived from a self-reported instrument, is prone to recall bias, leading to potential under-reporting of mood symptoms, especially severe depressive disorders.[80] Representativeness is another factor; individuals with a lifetime history of psychiatric disorders might have been less likely to participate in the UK Biobank study, potentially limiting the generalisability of the findings. Nevertheless, in view of the large sample size, diverse population characteristics, and heterogeneity in the environmental exposures, the effects on generalisability of the reported findings would have been minimal. The reported ORs of major depressive disorder might be further affected by finer design parameters of public green spaces, including size, shape, degree of landscaping, park facilities, and recreational programmes, which our study could not adjust for. Although the study included objectively measured metrics of residential green and physical environment, it could not individually adjust for perceptions of neighbourhood environment, including proxies of aesthetics and safety, which might influence usage of public green space.[81]

With rapid urbanisation and progressive urban densification, optimisation of individual-level exposures to green can be one of the most enduring public health interventions achieved by urban design and planning. Adding to previous evidence, our large-scale study concludes that exposure to green environments in an urban setting is associated with accrued psychological benefits in the form of reduced odds of major depressive disorders. This has substantial public health implications. As an upstream-level intervention, green environments, when optimally allocated, designed, and configured in relation to the existing matrix of land uses and the characteristics of the resident population, have the potential to enhance psychological ecosystem services and, subsequently, enhance the mental capital of cities.

Contributors

CS, CW, and JG conceived and designed the study. CS developed the built environment metrics, did the statistical analysis, and drafted the report. CS, CW, and JG contributed to redrafting and interpretations. All the authors read and approved the final manuscript.

Declaration of interests

We declare no competing interests.

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Title: Impact of Views to School Landscapes on Recovery from Stress and Mental Fatigue

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Introduction

Context impacts learning. It is well-documented, for instance, that physical characteristics of school environments such as lighting, noise, indoor air quality and thermal comfort, building age and condition all impact learning (Aturupane, Glewwe, & Wisniewski, 2013; Cheryan, Ziegler, Plaut, & Meltzoff, 2014; Roorda, Koomen, Spilt, & Oort, 2011). There is growing evidence that we have overlooked the impact school landscapes have on student academic performance. The cost of this oversight is that millions of children are trying to learn in settings that may be significantly less supportive than they might otherwise be.

Recent studies examining students' exposure to nature found the amount of vegetation within a campus significantly predicted school-wide student performance (i.e., standardized test scores, graduate rates) (Matsuoka, 2010; Wu et al., 2014). These exciting findings are correlational and thus the extent to which exposure to green school landscapes causes increased student performance remains unclear and unsubstantiated. We also do not know the mechanism or pathways through which green landscapes might influence student performance. Finally, if there is a causal relationship, we lack information regarding when the benefits of exposure to green campus landscapes might occur for students. The study reported here is designed to address these questions.

We begin by examining theory and evidence suggesting two possible pathways through which exposure to landscapes might result in better student performance—attention restoration and stress reduction. Next, we report a new study involving a randomized controlled experiment and end by discussing the implications of the findings for a variety of stakeholders.

Theoretical Framework on Nature and Student Performance

The Influence of Green Space on Children and Adolescents

Exposure to green space has been shown to have a variety of positive impacts on children and adolescents. These benefits include enhanced physical activity and play (Barton, Sandercock, Pretty, & Wood, 2014; Dyment & Bell, 2008), reduced chances of obesity and other chronic diseases (McCurdy, Winterbottom, Mehta, & Roberts, 2010), enhanced mental health and resilience (Chawla, Keena, Pevec, & Stanley, 2014; Corraliza & Collado, 2011; Flouri, Midouhas, & Joshi, 2014; Wells & Evans, 2003), improved environmental awareness (Chawla, 2009; Cheng & Monroe, 2012; Collado, Staats, & Corraliza, 2013; Wells & Lekies, 2006), and enhanced self-discipline and ability to concentrate (Faber Taylor & Kuo, 2009; Faber Taylor, Kuo, & Sullivan, 2002).

In education settings, recent studies have described a restorative effect associated with direct or indirect exposure to trees and other forms of vegetation on students across age groups. For elementary school students, the perceived restorativeness of school playgrounds is positively associated with vegetation volume and naturalness (Bagot, Allen, & Toukhsati, 2015; Collado & Corraliza, 2015). In a quasi-experimental study, middle school landscape renovation that increased the amount of vegetation was associated with reduced stress levels and enhanced psychological well-being (Kelz, Evans, & Röderer, 2013). Real and simulated views of natural elements were positively related to measures of attention and perceived restorativeness of college campus settings (Felsten, 2009; Laumann, Gärling, & Stormark, 2001; Tennessen & Cimprich, 1995). These studies suggest that students show objectively measured and anticipated restoration when exposed to greenness.

Green space offers restorative potentials, but to what extent does exposure to landscapes containing vegetation impact student performance? Two recent studies shed light on this question. One examined the relationship between vegetation condition surrounding schools and

school-based student performance on math and English as measured by the Massachusetts Comprehensive Assessment System and found a positive association between vegetation cover and academic performance (Wu et al., 2014). Another study measured high school environments including the amount of vegetation visible from classroom and cafeteria windows, the size of the windows, and the density of vegetation in each part of the campus, to predict student performance (i.e., standardized test scores, graduate rates, percentage of students planning to attend college). The findings demonstrated a positive relationship between nearby nature and school-wide academic performance (Matsuoka, 2010).

Although these two studies reveal a promising association between green campus landscapes and student academic performance, they are cross-sectional, correlational studies that cannot draw conclusions regarding the causal impact of greener campuses on student performance. It is possible, for instance, that these findings occur in part from self-selection. Perhaps more involved parents seek out greener settings and thus self-select into neighborhoods and school districts that have more trees. If this were the case, the association between exposure to green landscapes and student performance would be spurious. Thus, to determine if there is a causal link, we conducted a randomized controlled experiment to examine *how* green space affects academic performance. Why do students perform better when they were exposed to greener views? Two pathways seem most promising.

Possible Pathways between Landscape and Student Performance

Two theories have been proposed that might explain the effect of exposure to green landscapes on student performance: Attention Restoration Theory (ART) (Kaplan, Kaplan & Ryan, 1998; Kaplan, 1995) and Stress Reduction Theory (SRT) (Ulrich et al., 1991).

Sustained attention is the most important resource for learning. For students, inattention

often results in academic underachievement (Demaray & Jenkins, 2011; Rapport, Scanlan, & Denney, 1999), and access to nature has been demonstrated as crucial for restoring attentional capacities (Schutte, Torquati, & Beattie, 2015). Therefore, restored attention may be a pathway through which green landscapes lead to better performance.

ART proposes that people use voluntary control to inhibit distraction and remain focused, and this capacity to remain focused fatigues over time. After a short exposure to a green space, the cognitive capacity to focus attention is renewed because contact with nature enhances the inhibitory mechanism on which directed attention depends (Kaplan et al., 1998; Kaplan, 1995). Exposure to nature has been found to restore the cognitive resources supporting both executive functioning and self-regulation (Kaplan & Berman, 2010), which are also critical to learning.

Stress is predictive of reduced performance for children and adolescents. Studies have repeatedly shown that students who report lower personal and school-related stress attain higher GPAs (Gillock & Reyes, 1999), show more academic achievement (Grannis, 1992), and are less likely to engage in behaviors that lead to lower performance (e.g. truancy, dropping out of school) (Hess & Copeland, 2001). Therefore, reducing the stress that students experience might be a pathway through which green landscapes impact student performance.

SRT proposes that exposure to nature supports psychophysiological stress recovery, resulting in reduced blood pressure and lower levels of stress hormones (Ulrich et al., 1991). Recent studies also show positive physiological responses to nature including better neuroendocrine functioning (Van Den Berg & Custers, 2011), immune system functioning (Li, 2010), meditative brain wave activities (Aspinall, Mavros, Coyne, & Roe, 2013), and recovery from stressful experiences (Jiang, Chang, & Sullivan, 2014; Jiang, Li, Larsen, & Sullivan, 2014). A study involving elementary schools in Baltimore, Maryland, reported that students find green

school yards a safe retreat from stress, because the natural areas allow students to build competence and form supportive relationships (Chawla et al., 2014).

The possible relationship between attention restoration and stress recovery has been mentioned but not empirically tested. One theory is that attentional fatigue is an aftereffect of stress (Ulrich et al., 1991), and therefore the attentional restoration effect is based on emotional and physiological changes. Kaplan and Kaplan (1995), on the other hand, argue that stress can be caused by the human perception of inadequate resources. When one's attentional resources are reduced by a demanding task, an individual's appraisal of inadequacy may trigger physiological stress. To date, however, no research has tested the mediation effect of stress recovery on attention restoration, or vice versa. Therefore, in addition to testing the two potential pathways, we might advance our understanding of the relationship between these two mechanisms by testing the extent to which the relationship between green campus spaces and attention restoration depends on recovery from stress.

The Effect of Daylight on Student Performance

It is possible that the stress recovery and attention restoration effect of a window view, as well as student performance, is influenced by daylight entering the window (Collins, 1976; Plympton, Conway, & Epstein, 2000; Slopack, 2011; Zadeh, Shepley, Williams, & Chung, 2014) rather than, or in addition to, the greenness of the view. For many people, low levels of daylight can lead to seasonal depression, often called seasonal affective disorder (Beauchemin & Hays 1996). The symptoms of seasonal depression include sadness, anxiety, irritability, loss of interest in usual activities, withdrawal from social activities, and inability to concentrate (American Psychiatric Association, 2012). Clearly, these conditions are not conducive to learning.

Studies of daylighting in schools have demonstrated that full-spectrum daylighting in classrooms can promote overall health, reduce stress hormones, and enhance student performance (Küller & Lindsten, 1992; Nicklas & Bailey, 1997). These studies compared performance of students who learned in classrooms with different skylight and window light conditions. Thus, we wonder, is it enough to have access to daylight in classrooms or do views of green space enhance attentional functioning and help students recover from stressful experiences above and beyond exposure to daylight?

In order to examine the possible underlying mechanisms driving this relationship between campus greenness and student performance, we conducted an experiment using a randomized controlled design. We examined three main hypotheses – that views of green space from classrooms: 1) restores students' attentional functioning; 2) reduces students' stress levels; 3) reduces students' stress levels and restore attentional functioning above and beyond any effect from daylight. We also examine the magnitude and timing of the two effects, as well as the mediation effect of stress in the relationship between window view and attention.

Methods

Experiment Setting and Participants

Five public high schools in central Illinois were selected based on the criteria that they contained three classrooms that were identical in terms of room size, window size, lighting and furniture, but different in window views. To increase the generalizability of our findings, we selected two schools that were located in urban areas and three that were in suburban or rural areas. In each of the participating schools, we selected three classrooms for the experiment: a classroom with no windows, a classroom with windows that opened onto a built space, and a classroom with windows that opened onto a green space (Figure 1). Before the experiment, we

arranged the classrooms to ensure similar classroom layout.

Ninety-four high school students (53 female and 41 male) were randomly assigned to one of the three classrooms in the school where they attended. The no window, barren window and green window classroom conditions had 32, 30, and 30 participants respectively. The experiment was conducted with one student at a time between 9 am and 5 pm on sunny days with room temperatures approximately 70°F. All rooms had all lights turned on. After giving consent, participants reviewed the inclusion criteria to ensure that they had no major health conditions or drug use that would influence their physiological or cognitive performance. To account for any confounding variables, a general information questionnaire was administered to collect data about participants' age, gender, race, grade, health information, self-reported chronic stress levels, self-reported chronic mental fatigue, and preference for their school landscape.

Procedure

Each participant was randomly assigned to one of the three classrooms and completed the experiment with two examiners in the room. No other students or teachers were present during the experiment. All examiners were trained to follow the same experimental procedure, and they rotate to administer the three conditions. Students were instructed to sit in seats with identical orientation and distances to a window or, in rooms without windows, to the wall. To simulate classroom activities and induce moderate levels of stress and directed attention fatigue, all participants underwent a modified Trier Social Stress Test (TSST) procedure (Kirschbaum, Pirke, & Hellhammer, 1993). First, participants had a 5-minute rest (time 1: baseline). Then, they engaged in 30 minutes of classroom activities that included a proofreading task to find given sequences of letters in a page of random English letters, a speech task in which they were instructed to talk in front of two examiners about their dream job, and a subtraction task in which

they were given a four-digit number and asked to subtract 16 from that number, and then to continue subtracting 16 from each subsequent answer for five full minutes (time 2: class activity). They then had a 10-minute break during which they remained seated and awake in the classrooms (time 3: break). Questionnaires and attentional tests were administered at each time period.

Constructs and Measures

Attention

Subjective attention. Participants' baseline attentional functioning was assessed using a Visual Analogue Scale (VAS) questionnaire. VAS has been tested for construct validity and reliability, and has been shown to be well suited for the clinical assessment of self-reported psychological conditions (Lesage, Berjot & Deschamps, 2012). The VAS consisted of a 10-cm horizontal line. The left end of the line was marked "not at all" (0) and the right "extremely" (100). After hearing the instructions, participants placed a mark (X) on the line indicating the degree of mental fatigue they felt at that moment. By measuring the distance from the left end of the scale to the mark, we identified the value for the self-reported attention measure.

Objective attention. Participants were also asked to take the Digit Span Forward (DF) and the Digit Span Backward (DB) tests (Wechsler, 1981) of attentional functioning twice—once after the classroom activities, and once after the break. The DSF and DSB tests required participants to repeat increasing lengths of digit sequences in normal and reversed order until they make two consecutive failures. The tests have been used in a number of studies to assess attentional capacity, short-term memory and working memory (Yudofsky & Hales, 2008). We created a summary score for DSF and DSB to be used in the statistical analyses.

Stress

Subjective stress. Participants' baseline stress level was also assessed using a Visual Analogue Scale (VAS) questionnaire assessing the degree of stress they felt at that moment.

Objective stress. To record physiological measures of stress, participants were equipped with wrist and finger receivers of Electrocardiography (EKG) and Blood Volume Pulse (BVP), Skin Conductance Level (SCL) and body temperature (BT) throughout the experiment by the clinical biofeedback device Procomp Infiniti Physiological System. These measures are the most widely employed methods for measuring physiological stress, and are often used together in research related to exposure to nature and stress recovery (Jiang et al., 2014; Chang, Hammitt, Chen, Machnik & Su, 2008).

Heart rate measurement. Heart rate variability (HRV) was extracted from EKG and BVP data. Raw EKG data were reviewed to correct missed beats and extra beats. HRV represents the variation in the time interval between one heartbeat and the next (inter-beat interval), and has been shown to be one of the most reliable indicators of stress (Task Force of the European Society of Cardiology, 1996). The inter-beat interval (IBI) data were examined with Kubios HRV analysis software (University of Kuopio, Kuopio, Finland) to detect artifacts. Cubic spline interpolation was applied to replace missing IBI's. Data were also detrended using the smoothness priors method (Tarvainen et al., 2002). Time-domain measure pNN50 and frequency-domain measure LF/HF ratio were calculated at three times during the experiment. NN50 measures the number of pairs of successive normal inter-beat intervals that differ by more than 50 ms, with a smaller value indicating more stress and anxiety. pNN50 is the percentage of NN50 count within the total RR interval. LF/HF ratio is the ratio between the LF band power (0.04-0.15 Hz) and the HF band power (0.15-0.4 Hz), and a larger value indicates a hyper sympathetic nervous system which is related to increased acute stress and anxiety (Malik et al.,

1996).

Skin conductance level (SCL) and body temperature (BT) measurement. Skin conductance (SCL) and body temperature (BT) have also been widely used to measure mental stress in laboratory and real life settings (Healey & Picard, 2005). SC and BI were collected with a sampling rate of 2048 measurements per second. Raw SCL and BT data were processed to remove noise.

Control Variables

Since students' chronic levels of stress, mental fatigue and landscape preference might influence our acute measures of stress levels and attentional functioning, we included Likert scale questions assessing chronic stress, chronic mental fatigue and the extent to which participants preferred their campus landscape.

Results

Results are presented in four sections. First, we compare the baseline attention and stress levels among the three window-view groups to ensure there are no pre-treatment group differences. Second, we explore the effect of window view on students' ability to pay attention during class activities and after the break. Third, we examine the same window-view effects on students' stress levels during class activities and after the break. In the last section, we investigate the extent to which stress recovery mediates the relation between green view and attention restoration.

Baseline Attention and Stress

Were there differences among the baseline levels of attention and stress for students who were randomly assigned to the three window conditions? There are no significant differences in the baseline attentional functioning levels ($F=0.54$, $p=0.59$), stress levels ($F=0.98$, $p=0.38$),

chronic mental fatigue (F=1.33, p=0.27), chronic stress (F=1.13, p=0.33), or landscape preference (F=0.02, p=0.98) measures across the three groups at the beginning of the experiment. Overall, students' stress levels increased during the class activities and decreased after the break. Their attentional capacity declined during the class activities and rebounded after the break.

Effect of Window View on Attentional Functioning

To what extent did the window view effect students' attentional functioning during class activities and after the break? To answer this question, we created a summary attention score using two objective measures of attention, digits forward and digits backward, and examined the repeated-measures ANOVA result during the baseline, after class activities and after the break.

Did the window view affect attention? Yes, a repeated-measures ANOVA with window view as the between-subject factor and class activity and break as the within-subject factors revealed both significant main effects and an interaction. Students' capacity to pay attention decreased during class activities and increased after the break ($F_{1,90}$(time)=10.50, p<0.01, $\eta^2 = 0.10$). Second, the window views differed in terms of their impact on student attentional functioning ($F_{1,90}$(treatment)=4.43, p<0.05, $\eta^2 = 0.09$). Third, the recovery effects of performing the activities and having a break differed based on the window view ($F_{2,90}$(time*treatment)=11.14, p<0.001, $\eta^2 = 0.20$).

Did the difference in attentional capacity occur after class activities, or after the break? To answer this question, we conducted univariate ANOVAs examining the impact of window views at the end of class activities and after the break. There was no difference among the groups at the end of the class activities ($F_{2,90}$(activity)=0.51, p=0.60, $\eta^2 = 0.01$), but there was a significant difference at the end of break ($F_{2,90}$(break)=8.98, p<0.001, $\eta^2 = 0.17$) (Figure 1). The attentional capacity in the green window view condition was 14.33 percent higher than the

other two conditions combined.

Which window view condition caused the attention restoration effect? To answer this question, we made pairwise comparisons using Tukey's HSD (Tukey, 1949). The results demonstrate that after the break, the mean attention score for the green window view condition was significantly greater than the barren condition ($p<0.001$) and the no window condition ($p<0.01$). The barren and no window groups, however, showed no difference in attentional functioning after the break ($p=0.69$). Overall, students in the green window view condition demonstrated a 13.12 percent increase in attentional functioning.

What was the magnitude of the attention restoration effect after controlling for confounding variables? To answer this question, we regressed the change in attention scores (after break scores minus after class activity scores) onto the window view conditions (Table 1). The models controlled for demographic factors, chronic stress, chronic mental fatigue, and landscape preference. Taken together, these factors explained 18 percent of the variance in individual attention restoration (Model 1). After adding in classroom window view, the model improved significantly ($p<0.001$) and explained 31 percent of the total variance (Model 2). Students with green window views achieved attentional functioning restoration of 0.7 units higher than their peers who were randomly assigned to a barren window view, after controlling for the other variables. But the difference in attention restoration between the no window condition and the barren condition was not significantly different ($p=0.67$).

Effect of Window View on Stress

Does the window view have a significant effect on student's stress level during class activity and after the break as on attention restoration? To answer this question, we created a standardized summary physiological score (Cwir, Carr, Walton, & Spencer, 2011; Jiang, Chang,

& Sullivan, 2014; Rosenthal & Rosnow, 1991; Rutledge & Linden, 1998) from skin conductance (SC), body temperature (BT), percentage of NN50 (pNN50) and ratio between low-frequency peak and high frequency peak (LF/HF) and performed repeated-measures ANOVA.

The repeated-measures ANOVA results show the effect of window views at different points in the experiment. First, similar to the attention results, students' stress levels changed significantly during class activity and after the break ($F_{1,84}$(time)=19.6, p<0.0001, $\eta^2 = 0.19$). Considering all time periods, there was no significant difference in stress across the window view conditions (($F_{1,84}$(treatment)=1.93, p=0.15, $\eta^2 = 0.04$). There were, however, changes in stress levels across the three window view conditions, though the effect size was small and the effect was only marginally significant (($F_{2,84}$(treatment)=2.73, p=0.07, $\eta^2 = 0.06$) (Figure 2).

Because the time effect suggested stress recovery and the interaction effect was marginally significant, we compared the changes in stress levels (summary of changes of the four stress indicators) during class activities to the period immediately after the break across the groups using univariate ANOVA. The result showed a significant treatment effect in stress recovery ($F_{2,84}$(stress recovery)=3.69, p<0.05, $\eta^2 = 0.08$). Overall, the effect of window view on stress was similar to the pattern of change in attentional capacity, but the effect size was smaller.

To what extent did classroom window view predict stress recovery above and beyond demographic factors and baseline conditions? To answer this question, we regressed the summary stress recovery scores onto the environmental window conditions (see Table 1). Demographic factors, chronic stress, chronic mental fatigue, and preference explained 10 percent of the variation in stress reduction at the end of the break (Model 3). After adding in classroom window condition, the model significantly improved (p<0.05) and explained 17 percent of the

299 total variance (Model 2). Stress reduction in a green condition was 1.36 units higher than that of
300 the barren condition. But the comparison between no window and barren conditions was only
301 marginally significantly different (p=0.07).

302 **Did stress recovery mediate the relationship between window view and attention?**

303 In the analyses above, we found that window view caused significant variations in both
304 stress recovery and attention restoration. It is possible, therefore, as some have suggested (Ulrich
305 et al., 1991) that the impact of window view on attention restoration is mediated by stress
306 recovery. That is, the effect of window view on attention restoration may occur *through* stress
307 recovery. If this were the case, stress recovery should be systematically associated with attention
308 restoration. And adding in stress recovery in the regression model of window view predicting
309 attention restoration would make the attention pathway completely or partially disappear. To test
310 this possibility, we conducted a one-tailed Pearson Correlation and found that stress recovery and
311 attention scores are not correlated (r=.08, p =.23). Thus, in this study, stress reduction did not
312 mediate the relationship between window view and attention restoration.

313 **Discussion**

314 In this study, 94 students from five high schools were randomly assigned to classrooms
315 without windows, with windows that opened on to built space, and with windows that opened on
316 to green spaces. Students in the green window view condition scored significantly higher on tests
317 of attentional functioning and recovered significantly faster from a stressful experience than their
318 peers who were assigned to rooms without views to green spaces. Accounting for confounding
319 variables, the findings establish a causal relationship: green views produced better attentional
320 functioning and greater recovery from stress. We found no beneficial impact of daylighting alone.
321 Finally, there was no evidence that stress mediated the relation between view to green landscapes

and attention restoration, suggesting these are two distinct pathways influencing students' psychological and cognitive functioning.

Contributions

This is the first study to use a randomized controlled experimental design to examine the effect of views to green campus landscapes on students' attentional functioning and stress levels during class activities and breaks. Since sustained attention and free of stress have been proved to be critical for learning, our findings suggest the possible mechanism between greener campus and better student performance: green views promote attention restoration and recovery from stressful experiences. In this experiment, at the end of the class activities, there were no differences among the students in the three window view conditions with respect to attentional functioning or stress. But by the end of the break, students in the green window view condition performed significantly better on standard tests of attention and showed significantly greater stress recovery than their peers who were assigned to classrooms without a green view.

Why did a green view not result in higher attentional functioning and lower stress during classroom activities of the experiment? An explanation can be found in Kaplan's original article on ART which states that there are two ways of paying attention: voluntary and involuntary attention (Kaplan, 1995). During class activities, in order to focus their attention, students must ward off distractions by inhibiting stimuli in their surroundings and thoughts that compete for their attention. This inhibiting mechanism gets fatigued after prolonged mental effort (Kaplan & Berman, 2010). During the break, in the presence of green spaces visible through a window, involuntary attention is automatically activated and after a short period of time, as the inhibitory mechanism rests, a student's ability to focus attention is restored.

This study also reveals that exposure to nature impacts cognitive performance directly,

rather than through the mediation effect of stress. Although both processes occurred during this experiment when students had window views of a green space, the changes in attention and stress were not correlated.

Other studies have hinted at such a finding. For example, in an experimental study, the group assigned to view a nature video showed significant improvements in stress recovery but no improvement in attention scores (Laumann, Gärling, & Stormark, 2003). A study comparing the impact of walks in nature and urban environments reported significant impacts of the walks on physiological stress but not attention (Hartig, Evans, Jamner, Davis, & Gärling, 2003) The only previous study examining the association between changes in attention tasks and mood states revealed no correlation between the two, suggesting the cognitive and affective benefits from nature are due to different processes (Berman et al., 2012).

Attention restoration grows from the effortless attention-drawing character of nature (soft fascination) (Kaplan & Kaplan, 1989), which restores humans' ability to pay attention. Stress recovery is likely due to humans' readiness to respond affectively and physiologically to nature (Ulrich, 1993). The major difference of the two pathways is that attention restoration is based on cognition and the effect is through human cognitive operations, whereas stress recovery is based on affect and the effect is through physiological responses to stress.

The relationship between attention and stress is complex (Kaplan, 1995; Ulrich, 1993). Although the findings presented here demonstrate that stress and attention can occur independently, it is easy to imagine circumstances in which chronic stress can lead to attentional fatigue. Think, for instance, of a mother living in a dangerous setting who is constantly on the lookout for threats to her children. This mother is at risk of suffering chronic mental fatigue (Kuo, 2001). It also seems likely that mental fatigue can lead to stress – especially in anticipation of

inadequate mental resource (Kaplan, 1995). Ulrich goes one step further, however, and proposes that positive mood states can lead to attention restoration (Ulrich, 1993). The empirical findings testing this possibility are mixed. One study reported poorer cognitive control in positive mood states (Oaksford, Morris, Grainger, & Williams, 1996), while others have reported that positive mood states might promote attentional functioning associated with specific tasks that require creativity but not in tasks that require more focused attention (Ochsner & Gross, 2005; Phillips, Bull, Adams, & Fraser, 2002).

A stressful experience can even enhance attention under certain circumstances. The environmental rejection theory (Lacey, 1967; Lacey & Lacey, 1974; Lacey & Lacey, 1978) suggests that stressful mental tasks such as subtraction can accelerate heart rate, and in turn enhance one's capacity to resist distracting environmental stimuli (in other words, enhance directed attention).

Taken together, the findings presented in this paper and those from previous research suggest there are separate, demonstrated pathways from nature to enhanced attentional functioning and reduced stress, but inconclusive interrelationships between attention and stress.

In this study, we found that exposure to daylight had no impact on attentional functioning or stress recovery. That is, there were no statistically different outcomes between the classrooms with no windows and those that had window views that allowed natural daylight in but that looked out to built settings devoid of vegetation. These findings indicate that daylight is not a major factor underlying the relationship between window view and reduced stress and better attentional functioning. Thus, we should use caution when reviewing evidence on daylight and student performance or stress recovery, because the presence of green window views could be driving the different outcomes between window lighting conditions and no window conditions

(Plympton, Conway, & Epstein, 2000; Slopack, 2011).

Implications

The evidence presented here points to environmental factors that designers, planners, and policy makers can manipulate in order to enhance students' well-being and their likelihood of learning. We discuss the implications of these findings below.

School site selection

For planners working to identify sites for new schools, the result here suggest that sites that already have trees and other forms of vegetation are likely to have positive impacts on student learning. In the last few decades, there has been a dramatic shift in the location of high schools in North America. Whereas almost all high schools more than 50 years old are located in urban and suburban areas, almost all newer high schools (those less than 30 years old) are located at the rural-urban fringe or in rural areas. The hidden cost of siting schools on what was recently an agricultural field is that the lack of nearby trees will likely have negative consequences for learning. One easy solution is to be sure that a portion of the school design and development budget is reserved for site improvements that include planting a considerable number of trees on the site.

School ground and building design and renovation

Architects should work to ensure that every classroom has views to green space. Landscape architects should consider the locations of classroom, cafeteria and hallway windows in the development of their campus designs. Historically, campus design has been approached from the perspective of visitors to schools—landscape features are designed to enhance the view to the school and give visual identity to the main entrance. The findings of this study, however, indicate that campus landscapes should serve more purposes than merely aesthetic appeal, and

that designers should also consider the access to green space and green views from the angle of students and teachers who interact with the spaces on daily basis, especially those spaces that students and teachers interact with during their breaks. In addition to classroom views, views to green landscapes from hallways and the cafeteria seem particularly important. Providing views to green space in such areas will help students recover from mental fatigue and stress during their breaks and prepare students for their next class. Similarly, during renovations, designers should pay more attention to greening efforts on school grounds especially in areas where student activities and recess take place.

The views from classroom and cafeteria windows should be filled with natural features such as trees and shrubs. Classroom window views of large expanses of parking lots and athletic fields lacking natural elements should be minimized or screened by vegetation. Compared to most of the interventions aimed at relieving stress (e.g., emotional skill building, anger management, positive behavior programs), placing trees and shrubs on the school ground is a modest, low-cost intervention that is likely to have long-lasting effects on generations of students.

Further, our findings suggest a 10-minute break would suffice in restoring students' attentional capacities and help them recover from stressful tasks. School bell schedule should be designed to include short break periods to allow students to restore their attentional capacities.

Limitations and Future Research

To assess the effect of window view on student's stress level and attentional capacity, we carefully controlled a number of factors including setting, classroom activities, and break conditions (e.g., students remained seated during the break). This design, which allowed us to ensure that all participants received the same treatments, increased the internal validity of this

work. One limitation of such an approach, however, is that we could not take into account students' interactions, students' physical activities and their immersive experiences out on the school ground during the break, or their exposure to green space during physical education classes or after school. This limits the ecological validity of the findings presented here. Studies have demonstrated how immersive experiences in green school grounds help students recover from stress, build coping strategies, and form supportive social networks (Chawla et. al, 2014). Exercise in green space in school may also help students negotiate stress, regain attentional capacity and enhance mental health (Burdette & Whitaker2005). Future studies should examine how physical exposure to green schoolyards affect students' stress levels and attentional functioning. Future research might measure the combined impact of having green views from the school and green immersive experience, such as exercises on the school ground, on student performance.

The current study under-represents both the academic demands placed on students and the extent to which students may be exposed to green settings. A 40-minute experimental period far under-represents the academic and non-academic events that occur during an academic year that influence student's stress and attentional functioning. And the school ground is only one part of students' daily exposure to landscapes and thus cannot represent the variety or extent of landscapes to which students are exposed. Thus, future studies should expand the geographic and temporal aspects of landscape exposure and examine how other spaces impact student's psychological well-being and academic performance.

We made sure that the experiment resembled typical learning situations by including a 10-minute break in the study design. Most high schools in the US have breaks of 10 minutes or less. Clearly, a break of 10 minutes was long enough to demonstrate the impact of green views

on attention and stress. Would a longer break have shown a larger effect on stress recovery? Would increasing the frequency of breaks also show an effect? What is the effect of the interaction between the duration and frequency of breaks with green view on students' stress recovery and attention restoration? Future research should examine these possibilities.

It is also possible that the relationship between green views and stress recovery is not linear. That is, in the first few minutes of a green view, stress recovery may be slow, but over time, recovery may speed up. To our knowledge, no research has established the time-course of stress recovery associated with green views. This is a promising area for future research.

We found no differences in stress recovery or attention restoration for students randomly assigned to classrooms without windows and to classrooms with windows that allowed sunlight to enter but did not provide views to vegetation. We did not measure the intensity of sunlight or make any effort to ensure that the sunlight in either the barren window or green window condition was at all similar. This presents some slight threat to internal validity. Future research might explore the impact of varying levels of sunlight under barren and green conditions on stress recovery and attention restoration.

This study examined the effect of classroom window views on high school students. Although this study did not measure academic performance and therefore cannot fully explain the pathway from greenness to academic performance, the findings suggest that stress recovery and attention restorations are pathways through which school landscapes influence student performance. Future study can test the mediation effect of attention and stress on academic performance directly. The findings add to the evidence demonstrating that green views have powerful effects on the productivity of students at various ages (Faber Taylor & Kuo, 2009; Matsuoka, 2010; Wu, 2014). Since cognitive functioning is critical to understanding, learning

and performing different types of activities, views to green landscapes may also impact the productivity of workers (Bringslimark, Hartig, & Patil, 2007; Bringslimark, Patil, & Hartig, 2006). These pathways suggest rich possibilities for future studies.

Conclusions

We close by noting the importance of enhancing students' psychological and cognitive health by providing classrooms with green window views. This study demonstrated that classroom views to green landscapes have significant, positive impacts on recovery from stress and mental fatigue. These findings can provide guidance to parents, teachers, school administrators, architects, landscape architects, planners and policy makers interested in creating more supportive environments for learning.

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List of Tables

Table 1. Regression Analysis for Window View Conditions Predicting Attention Restoration and Stress Recovery

Individual Tables

Table 1. Regression Analysis for Window View Conditions Predicting Attention Restoration and Stress Recovery

Variables	Attention Model				Stress Model			
	Model 1		Model 2		Model 3		Model 4	
	B	SE	B	SE	SE	SE	B	SE
Intercept	-0.13	1.56	-0.10	1.46	-3.29	4.36	-4.26	4.27
Demographics								
Male	0.48**	0.17	0.46**	0.16	-0.19	0.48	-0.21	0.46
Age	0.04	0.09	0.00	0.09	0.15	0.26	0.13	0.26
Race								
African American	-0.01	0.21	0.16	0.20	-0.72	0.59	-0.42	0.59
Hispanic	-0.01	0.40	-0.10	0.38	0.49	1.23	0.21	1.21
Asian and Pacific Islander	-0.21	0.40	0.06	0.38	-0.39	1.08	-0.04	1.07
Other	-0.89*	0.37	-0.59+	0.35	-0.75	1.11	-0.13	1.10
Other Controls								
Chronic Stress Level	0.11	0.12	0.10	0.11	0.40	0.34	0.40	0.33
Chronic Attentional Problems	-0.31+	0.17	-0.20	0.16	-0.65	0.47	-0.48	0.46
Landscape Preference	-0.01	0.13	0.02	0.12	0.54	0.35	0.61^{+}	0.34
Treatment (barren view as reference)								
No Window			0.08	0.18			0.98^{+}	0.54
Green View			0.70***	0.20			1.36*	0.57
Stress Level change								
R2	0.18		0.31		0.10		0.17	
ΔR2			0.13***				0.07*	

+p<.1 *p<.05. **p<0.01. ***p<.001.

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Fig 1. Examples of classroom window view conditions: no window (left), windows opened on to built spaces (middle), and windows opened on to green space (right).

Fig 2. Attention scores at the end of class activity and break (Means and SE.).

Fig 3. Physiological stress at the end of class activity and break (Mean and SE.).



School No.1



School No.4

Figure 2

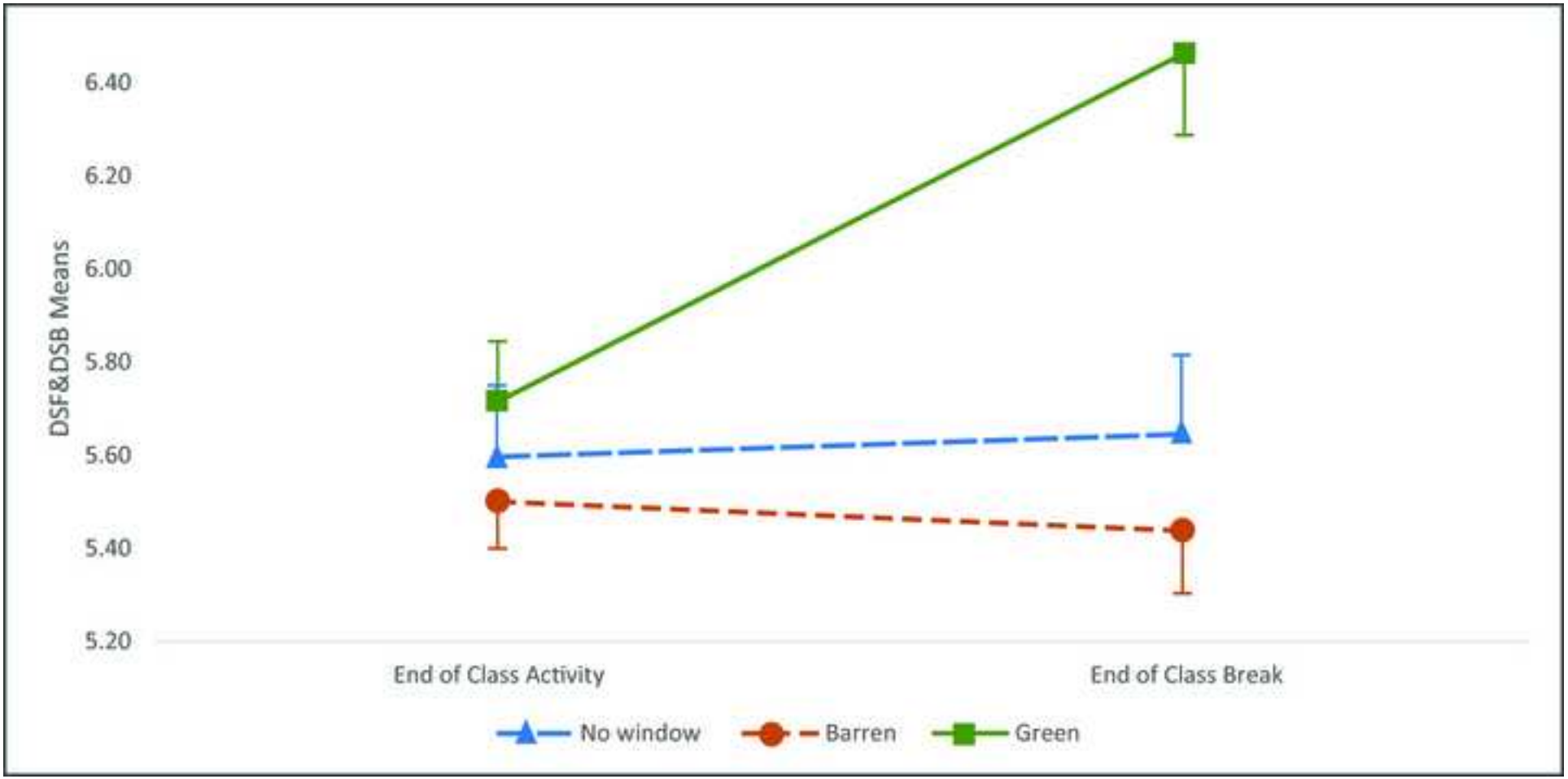
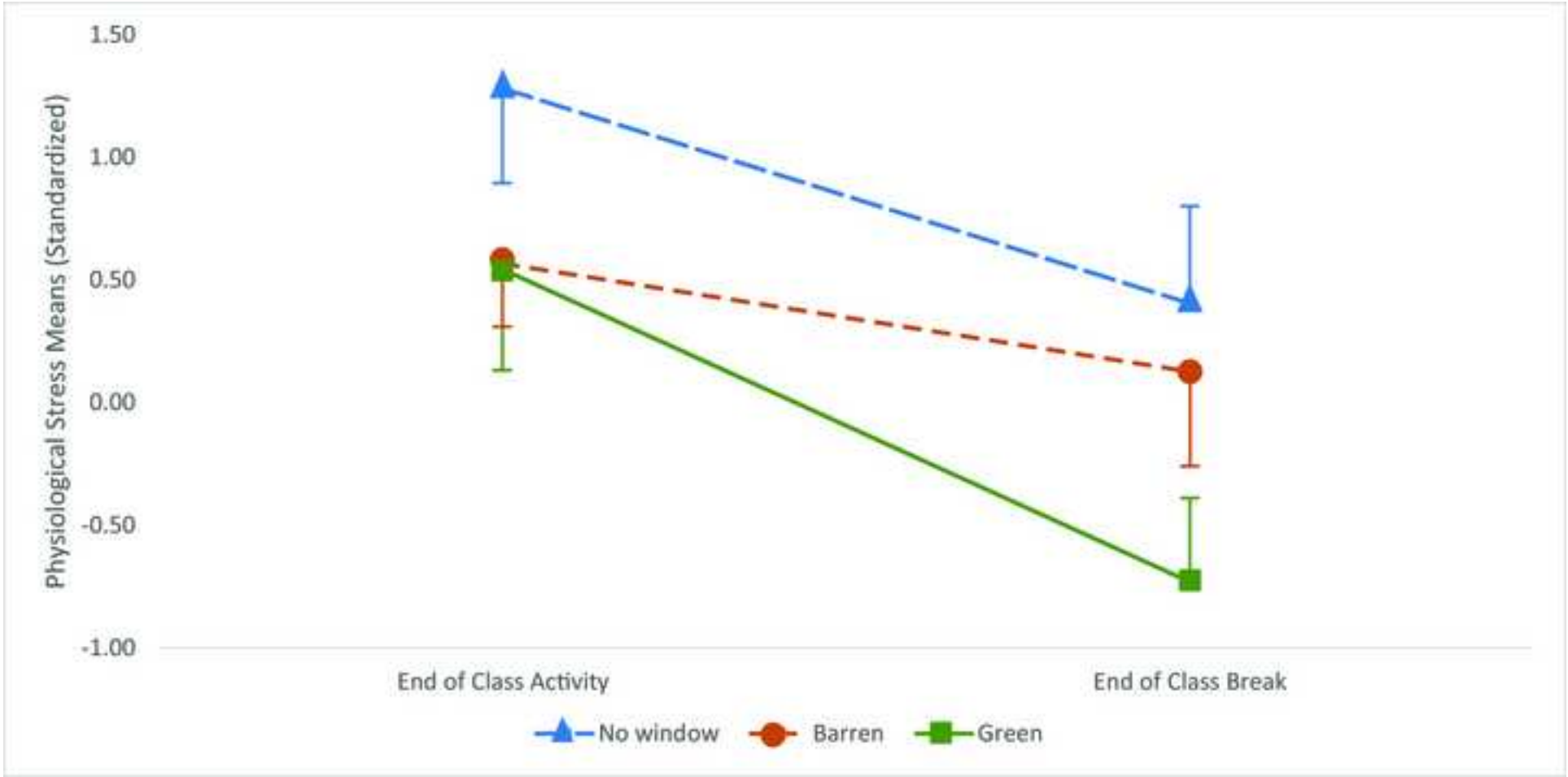

6.40
6.20
6.00
5.80
5.60
5.40
5.20
DSF&DSB Means
End of Class Activity
End of Class Break
No window
Barren
Green

Figure 3


1.50
1.00
0.50
0.00
-0.50
-1.00
Physiological Stress Means (Standardized)
End of Class Activity
End of Class Break
No window
Barren
Green

Green spaces and cognitive development in primary schoolchildren

[redacted]

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Exposure to green space has been associated with better physical and mental health. Although this exposure could also influence cognitive development in children, available epidemiological evidence on such an impact is scarce. This study aimed to assess the association between exposure to green space and measures of cognitive development in primary schoolchildren. This study was based on 2,593 schoolchildren in the second to fourth grades (7–10 y) of 36 primary schools in Barcelona, Spain (2012–2013). Cognitive development was assessed as 12-mo change in developmental trajectory of working memory, superior working memory, and inattentiveness by using four repeated (every 3 mo) computerized cognitive tests for each outcome. We assessed exposure to green space by characterizing outdoor surrounding greenness at home and school and during commuting by using high-resolution (5 m × 5 m) satellite data on greenness (normalized difference vegetation index). Multilevel modeling was used to estimate the associations between green spaces and cognitive development. We observed an enhanced 12-mo progress in working memory and superior working memory and a greater 12-mo reduction in inattentiveness associated with greenness within and surrounding school boundaries and with total surrounding greenness index (including greenness surrounding home, commuting route, and school). Adding a traffic-related air pollutant (elemental carbon) to models explained 20–65% of our estimated associations between school greenness and 12-mo cognitive development. Our study showed a beneficial association between exposure to green space and cognitive development among schoolchildren that was partly mediated by reduction in exposure to air pollution.

neurodevelopment | greenness | cognition | built environment | school

Contact with nature is thought to play a crucial and irreplaceable role in brain development (1, 2). Natural environments including green spaces provide children with unique opportunities such as inciting engagement, risk taking, discovery, creativity, mastery and control, strengthening sense of self, inspiring basic emotional states including sense of wonder, and enhancing psychological restoration, which are suggested to influence positively different aspects of cognitive development (1–3). Beneficial effects of green spaces on cognitive development might accrue from direct influences such as those above, with green space itself exerting the positive influence or through indirect, mediated pathways. The ability of green spaces to mitigate traffic-related air pollution (TRAP) (4) could lead to a beneficial impact of green spaces on cognitive development, because exposure to TRAP has been negatively associated with cognitive development in children (5). Further to TRAP, green spaces can also reduce noise (6), which itself too has been negatively associated with cognitive development (7). Moreover, proximity to green spaces, particularly parks, has been suggested to increase physical activity (8), and higher levels of physical activity are related to improved cognitive development (9). Outdoor surrounding greenness has also been reported to enrich microbial input from the environment (10), which may positively influence cognitive development (10). Through these pathways, exposure to green space, including outdoor surrounding greenness and proximity to green spaces, could influence cognitive development in children, yet the available population-based evidence on the association between such exposure and cognitive development in children remains scarce.

The brain develops steadily during prenatal and early postnatal periods, which are considered as the most vulnerable windows for effects of environmental exposures (11). However, some cognitive functions closely related with learning and school achievement—such as working memory and attention—develop across childhood and adolescence as an essential part of cognitive maturation (12–14). We therefore hypothesized a priori that exposure to green space in primary schoolchildren could enhance cognitive development. Accordingly, our study aimed to assess the association between indicators of exposure to green space and measures of cognitive development, including working memory (the system that holds multiple pieces of transitory information in the mind where they can be manipulated), superior working memory (working memory that involves continuous updating of the working memory buffer), and inattentiveness in primary schoolchildren. As a secondary aim, we also evaluated the mediating role of a reduction in air pollution as one of the potential mechanisms underlying this association.

Significance

Green spaces have a range of health benefits, but little is known in relation to cognitive development in children. This study, based on comprehensive characterization of outdoor surrounding greenness (at home, school, and during commuting) and repeated computerized cognitive tests in schoolchildren, found an improvement in cognitive development associated with surrounding greenness, particularly with greenness at schools. This association was partly mediated by reductions in air pollution. Our findings provide policymakers with evidence for feasible and achievable targeted interventions such as improving green spaces at schools to attain improvements in mental capital at population level.

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ENVIRONMENTAL SCIENCES

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Methods

Study Setting. We undertook this study in Barcelona, Spain, a port city situated on the northeastern part of the Iberian Peninsula. It has a Mediterranean climate characterized by hot and dry summers, mild winters, and maximum precipitation and vegetation during autumn and spring. This study was conducted in the context of the brain development and air pollution ultrafine particles in school children (BREATHE) project. Of the 416 schools in Barcelona, 37 schools were initially selected to obtain maximum contrast in TRAP levels (i.e., nitrogen dioxide: NO_2), of which 36 accepted to participate and were included in the study (*SI Appendix*, Fig. S1). Participating schools were similar to the remaining schools in Barcelona in terms of the neighborhood socioeconomic vulnerability index (0.46 versus 0.50, Kruskal–Wallis test $P = 0.57$) and NO_2 levels (51.5 versus 50.9 $\mu g/m^3$, Kruskal–Wallis test $P = 0.72$).

All schoolchildren ($n = 4{,}562$) without special needs in the second to fourth grades (7–10 y) of these schools were invited to participate by letters or presentations in schools for parents, of which 2,623 (58%) agreed to take part in BREATHE. All children had been in the school for more than 6 mo (and 98% more than 1 y) before the beginning of the study. All parents or guardians signed the informed consent and the study was approved (No. 2010/41221/I) by the Clinical Research Ethical Committee of the Parc de Salut Mar, Barcelona.

Outcome: Cognitive Development. Cognitive development was assessed through 12-mo change in developmental trajectory of working memory and attention. We selected these functions because they grow steadily during preadolescence (15, 16). We used computerized *n*-back test for assessing working memory (15) and computerized attentional network test (ANT) (17) for evaluating attention.

From January 2012 to March 2013, children were evaluated every 3 mo over four repeated visits by using computerized tests in sessions lasting ~40 min in length. Groups of 10–20 children wearing ear protectors were assessed together and supervised by one trained examiner per 3–4 children. For the *n*-back test, we examined different *n*-back loads (up to three-back) and stimuli (colors, numbers, letters, and words). For analysis here, we selected both two-back and three-back loads for number and word stimuli because they showed a clear age-dependent slope in the four measurements (4). The two-back predicts general mental abilities (i.e., working memory) whereas the three-back also predicts superior functions such as fluid intelligence (i.e., superior working memory) (18). All sets of *n*-back tests started with colors as a training phase to ensure participants' comprehension of the test. The *n*-back parameter analyzed was *d* prime (d'), a measure of detection subtracting the normalized false alarm rate from the hit rate [(Z hit rate − Z false alarm rate) ×100]. A higher d' indicates more accurate test performance. Given that our final findings for numbers and words were similar, here we only show results for numbers. Among the ANT measures, we chose hit reaction time standard error (HRT-SE) (SE of RT for correct responses), a measure of response speed consistency throughout the test (19), because it showed a clear growth during the 1-y study period. A higher HRT-SE indicates highly variable reactions related to inattentiveness.

Exposure to Green Space. Our assessment of exposure to green space was based on a comprehensive characterization of outdoor surrounding greenness (photosynthetically active vegetation) encompassing greenness surrounding home, greenness surrounding commuting route between home and school (hereafter referred to as commuting greenness), and greenness within and around school boundaries.

To assess outdoor surrounding greenness we applied normalized difference vegetation index (NDVI) derived from RapidEye data at 5 m × 5 m resolution. NDVI is an indicator of greenness based on land surface reflectance of visible (red) and near-infrared parts of spectrum (20). It ranges between −1 and 1, with higher numbers indicating more greenness. The RapidEye Imagery is acquired from a constellation of five satellites 630 km above ground in sun-synchronous orbits. We generated our NDVI map by using the image obtained on July 23, 2012, that was available for our study region during our study period (*SI Appendix*, Fig. S1).

Residential surrounding greenness. Residential surrounding greenness was abstracted as the average of NDVI in a buffer of 250 m (21, 22) around the home address of each study participant. For 174 children (5.9%) who shared two homes, we used the address where the child spent most of her/his time.

Commuting greenness. Data on the main mode of commute to and from school was obtained from parents via questionnaires. Approximately 60% of participants reported walking as the main mode of commuting, whereas the 38% reported commuting by motor vehicles (private car, bus, motorcycle, or tram). The remaining 2% reported the underground metro train as the main mode of transport, for whom we assumed no exposure to greenness during commuting. For participants reporting walking as the main mode of commuting, we identified the shortest walking route to school and for participants reporting motor vehicles as the main mode of commuting, we identified the shortest driving route to school, based on street networks (network distance) by using network analyst extension from ArcGIS software v10. We defined commuting greenness as the average of NDVI in a 50-m buffer around the commuting route.

School greenness. To assess greenness within school premises, we first digitized the school boundaries and then averaged NDVI values within those boundaries. To assess greenness surrounding schools, we averaged NDVI values across a 50 m buffer around the school boundaries.

Total surrounding greenness index. We developed a total surrounding greenness index by averaging residential surrounding greenness (250-m buffer), commuting greenness, and greenness within school boundaries weighted by the daytime (12 h a day) that children were assumed to spend at home (3 h), commuting (1 h), and school (8 h). To avoid double-counting in developing this index, we abstracted as the average NDVI over commute corridor beyond the 250-m home buffer and 50-m school buffer.

Main Analyses. Data on 9,357 tests from 2,593 (99%) children were available for analysis. Because of the multilevel nature of the data (i.e., multiple visits for each child within schools), we used linear mixed effects models with the four repeated cognitive parameters as outcomes (one test at a time), each measure of exposure to green space (one at a time) as fixed effect predictor, and child and school as random effects (5). An interaction between age at each visit and the indicator of exposure to green space was included to capture changes in 12-mo progress in cognitive trajectory associated with greenness exposure (5). The main effect of exposure to green space, which was also included in the model, captured the baseline (visit 1) differences in cognitive function that were associated with exposure to green space before the first visit. This model was further adjusted for potential confounders identified a priori*:* age (centered at visit 1), sex, and indicators of socioeconomic status (SES) at both individual and area levels. Maternal education (no or primary/secondary/university) was used as the indicator of individual-level SES and Urban Vulnerability Index (23), a measure of neighborhood SES at the census tract (median area of 0.08 km^2 for the study region) was applied as the indicator of area-level SES. Linearity of the relation between exposure to green space and cognitive tests was assumed because generalized additive mixed models did not show any nonlinearity of associations. We estimated the change in average outcome scores associated with one interquartile range (IQR) increase (based on all study participants) in average NDVI. Statistical significance was set at $P < 0.05$. R statistical package was used to carry out the analyses.

Mediating Role of Traffic-Related Air Pollution. We hypothesized that reduction in TRAP levels could be one of the potential mechanisms underlying the association between greenness exposure and cognitive development. To quantify such a mediating role, we calculated the percent of the associations between greenness and cognitive development explained by TRAP as $[1 - (\beta_{gm}/\beta_g)] \times 100$, where β_{gm} was the regression coefficient for the greenness exposure in a fully adjusted model including the mediator (i.e., TRAP) and β_g was the regression coefficient in the fully adjusted model without including the mediator (24).

We focused on the associations between school greenness and cognitive development because they were the strongest among our evaluated associations (*Results*) and also because of the availability of data on levels of air pollutants at BREATHE schools that were monitored as part of the BREATHE project. Such a high-quality monitored data were not available for TRAP levels at homes or during commuting. Among the TRAPs monitored in the BREATHE framework, we chose indoor levels of elemental carbon (EC) for this mediation analyses. EC is mainly generated by fossil fuel combustion and is considered as a tracer of road traffic emissions in Barcelona (25). In other BREATHE analyses, we had observed that indoor EC was associated with adverse impacts on cognitive development (5) and EC levels were reduced in schools with higher greenness (4). Detailed description of TRAP sampling methodology at the BREATHE schools has been published (25, 26).

Results

Children were on average 8.5 y old at baseline and 50% were girls. Regarding maternal education, 13% of mothers had no or only primary school, 29% secondary school, and 58% university education. Further characteristics of the study participants are presented in *SI Appendix*, Table S1. Average working memory increased by 22.8%, superior working memory by 15.2%, and

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inattentiveness decreased by 18.9% during the follow up (Table 1). At baseline, higher maternal education was associated with better cognitive function (*SI Appendix*, Table S2). For 12-mo progress, whereas higher maternal education was associated with larger reduction in inattentiveness, improvements in working memory and superior working memory were not associated with maternal education (*SI Appendix*, Table S2). The median (IQR) of our estimated surrounding greenness for all participants and across strata of maternal education are presented in Table 2 and *SI Appendix*, Table S2, respectively. The Spearman's correlation coefficient among residential, school, and commuting surrounding greenness varied from 0.46 (between surrounding greenness at home and greenness within school boundaries) to 0.80 (between commuting and school surrounding greenness) (*SI Appendix*, Table S3).

Main Analyses. We observed an enhanced 12-mo progress in working memory and superior working memory and a greater 12-mo reduction in inattentiveness associated with greenness within and surrounding school boundaries and with the total surrounding greenness index (Table 2, Fig. 1, and *SI Appendix*, Fig. S2). Commuting greenness was also associated with improved 12-mo progress in working memory and superior working memory, although the association for superior working memory was only marginally statistically significant. We did not observe any association between residential surrounding greenness and cognitive measurements (Table 2). None of the indicators of outdoor greenness were associated with baseline cognitive measurements (Table 2).

The findings for *n*-back tests with "word" stimuli were consistent with the aforementioned results for "number" stimuli (*SI Appendix*, Table S4). The association between commuting greenness and 12-mo progress in superior working memory, which had borderline statistical significance for the three-back test using number stimuli, was statistically significant for the test using word stimuli.

To explore the possibility of an impact of green space exposure on other ANT measures than inattentiveness, we repeated the main analyses by using alerting, orienting, and executive processing (one at a time) abstracted from ANT as outcome. We did not observe any statistically significant association for these outcomes with any of indicators of green space exposure (*SI Appendix*, Table S5), which was consistent with our observation that these measures did not show any clear growth during the study period.

We conducted a number of sensitivity analyses as described in *SI Appendix* that showed the robustness of our findings to alternative definition of total surrounding greenness index and commuting greenness and to including a range of relevant covariates in models (e.g., socioeconomic indicators and condition of venue at the time of cognitive tests).

Mediating Role of Traffic-Related Air Pollution. The Spearman's correlation coefficients between school EC levels and greenness within and surrounding school boundaries were −0.62 and −0.66 ($P < 0.01$), respectively. Adding EC to models explained 20–65% of associations between school greenness and 12-mo progress in cognitive functions (Table 3). Including EC reduced effect sizes in all models. EC made the associations between school surrounding greenness and superior working memory and between greenness within and surrounding school boundaries and inattentiveness much smaller and statistically nonsignificant (Table 3).

Discussion

To our knowledge, this is the first epidemiological study to report on the impact of exposure to green space on cognitive development in schoolchildren. School and total surrounding greenness index were associated with enhanced 12-mo progress in indicators of working memory and superior working memory and greater 12-mo reduction in inattentiveness. Commuting greenness was also associated with better 12-mo progress in working memory. Adding EC to our models explained 20–65% of our estimated associations between green spaces and 12-mo cognitive development.

Interpretation of Results. Over a 12-mo period, we observed that an IQR exposure increment in total surrounding greenness index was associated with a 5% increase in the progress of working memory, a 6% increase in the progress of the superior working memory, and a 1% reduction of inattentiveness. Among our assessed exposure measures, we observed the strongest associations for greenness within or surrounding school boundaries. Children spend a considerable part of their active daily time at schools and "green exercise" has been related to better mental health (27). Furthermore, the combination of physical activity in school with daily peaks of TRAPs in urban areas that often coincide with school time could result in a considerable inhaled dose of air pollutants at school. Consistently, in our other BREATHE analysis of the impact of TRAPs on cognitive development using the same measures of cognitive development as in this study, we also observed stronger associations for levels at school compared with those at home (5). Therefore, the ability of school greenness in reducing pollutant levels (4) might explain, in part, why we observed the strongest associations for school greenness.

We found some indications for an enhanced 12-mo progress in working memory associated with commuting greenness. Because of the strong correlation between greenness surrounding school boundaries and commuting greenness, it was not possible to determine the independent impact of commuting greenness (i.e., whether commuting greenness is a surrogate for school surrounding greenness). Therefore, our findings for commuting greenness should be interpreted with caution. To the best of our knowledge, this study is the first reporting on the potential impact of commuting greenness on health in general and on cognitive development in particular. We hypothesize that green exercise and visual access to greenness might underlie such an association, if any.

The beneficial associations for 12-mo progress in cognitive functions were stronger than those at baseline. Baseline estimates reflected the association between cognitive test scores at the first visit and the cumulative green space exposure preceding the study period, whereas our exposure assessment was based

Table 1. Description of the cognitive outcomes in children [median (25th–75th %)]

Visit	*n*	Age (mean), y	Working memory (WM) (two-back numbers), d′*	Superior WM (three-back numbers), d′*	Inattentiveness (ANT HRT-SE)†, ms
First visit	2,278	8.5	206 (129, 360)	112 (53, 171)	271 (205, 338)
Second visit	2,425	8.7	221 (129, 392)	112 (59, 190)	250 (186, 321)
Third visit	2,347	9.1	234 (129, 392)	128 (59, 190)	247 (183, 317)
Fourth visit	2,307	9.4	253 (152, 392)	129 (64, 210)	228 (165, 294)

*The *n*-back *d′* is a measure of detection subtracting the normalized false alarm rate from the hit rate [(Z hit rate − Z false alarm rate) × 100].
†Hit reaction time SE (HRT-SE), SE of reaction time for correct responses as a measure of response speed consistency throughout the test.

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Table 2. Adjusted difference (95% confidence interval) in baseline and 12-mo progress of working memory, superior working memory, and inattentiveness per one interquartile range (IQR) change in greenness

		Working memory† (2-back number stimuli, d′)		Superior working memory† (3-back number stimuli, d′)		Inattentiveness† (HRT-SE, ms)	
Surrounding greenness	Median (IQR)	Baseline	Progress	Baseline	Progress	Baseline	Progress
Home	0.091 (0.053)	0.2 (-3.8, 4.2)	0.7 (-2.6, 4.1)	0.6 (-2.5, 3.7)	−0.1 (-2.7, 2.6)	2.0 (-1.4, 5.4)	−0.7 (-3.1, 1.7)
School							
Within	0.094 (0.085)	0.3 (−6.8, 7.4)	9.8 (5.2, 14.0)*	0.9 (−5.0, 6.8)	6.9 (3.4, 10.0)*	−4.0 (−12.0, 4.0)	−3.4 (−6.6, −0.2)*
Surrounding‡	0.100 (0.120)	3.2 (−4.3, 11)	9.5 (4.5, 15.0)*	1.5 (−4.8, 7.8)	6.3 (2.3, 10.0)*	−5.1 (−14.0, 3.6)	−3.7 (−7.3, −0.1)*
Commuting	0.100 (0.062)	1.5 (−3.5, 6.6)	4.9 (1.0, 8.8) *	3.5 (−0.6, 7.5)	3.1 (0.0, 6.1)	0.2 (−4.5, 4.9)	−1.2 (−4.0, 1.7)
Total surrounding greenness index	0.094 (0.073)	0.0 (−6.9, 6.5)	9.8 (5.0, 15.0)*	1.7 (−4.4, 7.8)	6.7 (2.8, 11.0)*	−2.4 (−9.8, 4.9)	−3.9 (−7.4, −0.4)*

*$P < 0.05$.
†Difference adjusted for age, sex, maternal education, and residential neighborhood socioeconomic status with school and subject as nested random effects.
‡Fifty-meter buffer around school boundaries.

on the home address of participants and the school they were attending during the study period, not including potential prior different addresses or schools to their current ones. Part of our observed larger estimates for 12-mo progress might therefore reflect better characterization of exposure, but it could also be due to the window of vulnerability for these high executive functions that develop significantly during the primary school age (12–14). This window of vulnerability might also explain why we observed the strongest associations for 12-mo progress in superior working memory that develops considerably during this period.

We did not observe any statistically significant difference in 12-mo progress in working memory and superior working memory (for which we found associations with green space exposure) between strata of maternal education. Moreover, further adjustment of our analyses for other indicators of SES like parental employment, marital status, and ethnicity (*SI Appendix, SI Methods*) did not change the interpretation of our findings notably. Furthermore, removing SES indicators (maternal education and neighborhood SES) from our fully adjusted models did not result in a considerable change in the interpretation of our findings (*SI Appendix*, Table S6). Additionally, we did not observe any statistically significant effect modification by maternal education or neighborhood SES for our associations ($P > 0.1$). These observations might suggest that our results were unlikely to have been affected by residual SES confounding.

Available Evidence and Potential Underlying Mechanisms. We are not aware of previous epidemiological studies on the impact of green space exposure on cognitive development in schoolchildren; therefore, it is not possible to compare our findings with those of others. Our findings, however, are consistent with several previous observations. Residential surrounding greenness has been related to better mental health including lower risk of depression and anxiety in children (28). Higher school greenness has been associated with better student performance at schools (29). Experimental studies have shown walking in nature or watching photos of nature could improve directed-attention abilities in adults (30) and have "therapeutic effects" on attention deficit hyperactivity disorder symptoms in children (31–34). Our previous cross-sectional analysis of BREATHE participants showed a protective impact of home and school greenness on behavioral problems including hyperactivity and inattention (35). That analysis was based on behavioral screening questionnaires rated by teachers and parents. In those questionnaires behavioral aspects that characterized hyperactivity/inattention were modestly correlated (Spearman's correlation coefficients ranging between 0.18 and 0.23) with the ANT inattentiveness score (at baseline) used in this study. A study by Wells (2000) reported that relocation to residences with higher "naturalness" improved cognitive function in a sample of 17 children (36). In an analysis of BREATHE schools, we observed that higher greenness inside and surrounding school boundaries was associated with lower TRAPs levels at schools (5), in line with our other study showing lower levels of personal exposure to TRAPs (based on personal monitors) associated with higher residential surrounding greenness in Barcelona (22). Another BREATHE analysis, using the same cognitive measures as the current study, demonstrated that higher levels of TRAPs at school were associated with diminished 12-mo cognitive progress (5). Thus, reduction of exposure to TRAPs associated with higher greenness could have partly underlain our observed associations. Consistently, in the current analysis we observed that including a TRAP (EC) in our models could explain one-fifth to two-thirds of the associations, suggesting that our observed beneficial associations between greenness exposure and cognitive development could have been partly mediated by reduction in exposure to TRAPs. These findings could also suggest that other mechanisms may account for 35–80% of our observed associations that was not explained by reduction in TRAP exposure. Higher ambient noise has been related with adverse impacts on cognitive development (7). The ability of green spaces to

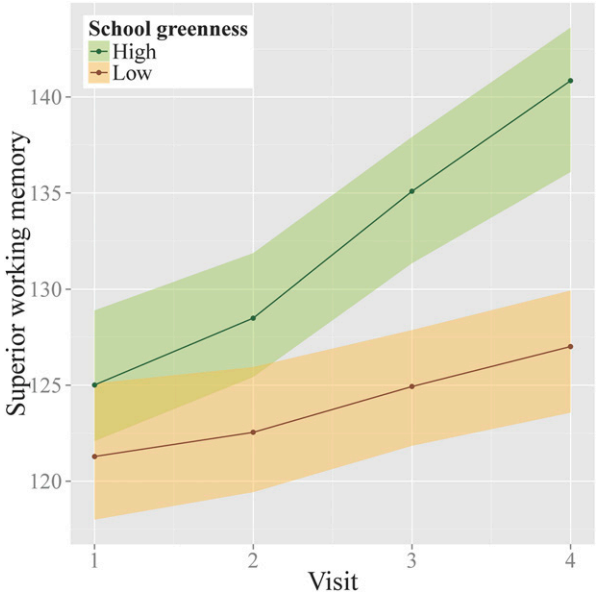


Fig. 1. Twelve-month progress (with 95% confidence bands) in superior working memory for participants with the first (low greenness) and third (high greenness) tertiles of greenness within the school boundaries.

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Table 3. Difference (95% confidence interval) in 12-mo cognitive trajectory per one interquartile range change in greenness estimated by main analyses and models further including school indoor elemental carbon (EC) interaction with age

Outcomes/exposures	Main analyses[†,‡]	Further adjusted for EC[‡]	% explained
Working memory			
Within school	9.8 (5.2, 14.0)*	8.7 (2.5, 15.0)*	20.4
Surrounding school	9.5 (4.5, 15.0)*	6.9 (0.9, 13.0)*	27.4
Superior working memory			
Within school	6.9 (3.4, 10.0)*	4.9 (0.1, 9.8)*	29.0
Surrounding school[§]	6.3 (2.3, 10.0)*	3.3 (-1.5, 8.1)	47.6
Inattentiveness			
Within school	−3.4 (-6.6, -0.2)*	−1.2 (-5.6, 3.2)	64.7
Surrounding school	−3.7 (-7.3, -0.1)*	−1.8 (-6.1, 2.5)	51.4

*$P < 0.05$.
[†]Adjusted for age, sex, maternal education, and residential neighborhood socioeconomic status with school and subject as nested random effects.
[‡]Estimates per 0.085 and 0.120 change respectively in greenness within and surrounding school boundaries (i.e., 1-interquartile change).
[§]Fifty-meter buffer around school boundaries.

reduce noise (6) might therefore explain a part of our observed associations (37). Moreover, proximity to green spaces has been reported to increase physical activity (38), and physical activity has been associated with better cognitive function in children (9). Furthermore, parental psychological stress and depression have been reported to be adversely associated with cognitive development in their children (39) and exposure to green space has been associated with evidence of stress restorative effects and reduced depression in adults (3, 28). A growing body of evidence also suggests that a failure of the immunoregulatory pathways due to a reduced exposure to macroorganisms and microorganisms in Westernized populations might play a role in impairment of brain development (10, 40) with childhood as a particular window of vulnerability (41). Therefore, the ability of outdoor surrounding greenness to enhance immunoregulation-inducing microbial input from the environment (10) could have been another mechanism underlying our observed association between greenness exposure and cognitive development.

Implications for Policymakers. Approximately one-half of the world population lives in cities, and it is projected that by 2030, three of every five persons will live in urban areas worldwide (42). Urban areas are characterized by a network of nonnatural built-up infrastructures with increased pollutant levels and less green environments (43). Children's exposure to these pollutants such as air pollution and noise has been associated with detrimental impacts on their cognitive development. Our findings suggest for a beneficial impact of green space exposure on cognitive development, with part of this effect resulting from buffering against such urban environmental pollutants. This impact was more evident for surrounding greenness at school and for working memory and superior working memory, which are predictors of learning and academic attainment (44). Schoolchildren with a superior working memory progress of less than one-10th of a percentile (45) of the distribution can be classified as impaired superior working memory progress. Our results suggest that if schools increased greenness within their boundaries by the observed IQR (Fig. 1), then 8.8% of children with impaired superior working memory progress would move out of this category. Our findings, therefore, hold importance for policymakers when translating evidence into feasible and achievable targeted interventions such as improving greenness at schools, given that improved cognitive development in children attending schools with more greenness could result in an advantage in mental capital, which, in turn, would have lasting effects through the life-course.

Strengths and Limitations of Study. This study was based on repeated computerized tests of cognitive development to quantify different aspects of cognitive development in study participants. These tests have been reported to have acceptable internal consistency, reasonable factorial structure, and good criterion validity and statistical dependencies for use in general population (46). We applied one of the most comprehensive approaches to date to assess exposure to green space by characterizing the outdoor surrounding greenness at home and school and during commuting by using high-resolution (5 m × 5 m) satellite data on greenness, enabling us to account for small-area green spaces (e.g., home gardens, street trees, and green verges) in a standardized way.

Our study also faced some limitations. The generalizability of our findings might have been affected by selection bias in that those participants participated in BREATHE were different from those not participated with respect to SES. Approximately 58% of mothers in our study population had a university degree, which was higher that the regional average of 50% among women between 25 and 39 y old living in Barcelona (47). We did not, however, observe any indication of effect modification by maternal education in our associations. Moreover, the Urban Vulnerability Index of the schools was not associated with school participation rate (Spearman's correlation coefficient = −0.09, $P = 0.61$); these observations might suggest that the socioeconomic status was less likely to be a major predictor of participating in the study. Similarly, school greenness was not associated with participation rate at schools (Spearman's correlation coefficients of −0.06 with P value = 0.72 for greenness within school boundaries and 0.13 with P value = 0.43 for greenness surrounding schools). Our exposure assessment focused on exposure during the school age, overlooking other potential windows of susceptibility such as prenatal and preschool periods. Investigating these windows of susceptibility presents an opportunity for future studies. By using an NDVI map obtained at a single point in time (2012), we effectively assumed that the spatial distribution of NDVI across our study region remained constant over the study period (2012). The findings of our previous studies support the stability of the NDVI spatial contrast over seasons and years (21, 48). Finally, data were not available for some potentially relevant confounders, such as parental mental health status.

Conclusions

Exposure to outdoor surrounding greenness was associated with a beneficial impact on cognitive development in schoolchildren.

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These associations were only partly mediated by reduction in TRAP levels, suggesting that other mechanisms likely underlie this association. Our observed beneficial associations were consistent for working memory, superior working memory, and inattentiveness and were more evident for greenness at school. Further studies are warranted to replicate our findings in other settings with different climates and to investigate other cognitive functions with different windows of susceptibility such as prenatal and preschool periods.

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THE RESTORATIVE BENEFITS OF NATURE: TOWARD AN INTEGRATIVE FRAMEWORK

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Abstract

Directed attention plays an important role in human information processing; its fatigue, in turn, has far-reaching consequences. Attention Restoration Theory provides an analysis of the kinds of experiences that lead to recovery from such fatigue. Natural environments turn out to be particularly rich in the characteristics necessary for restorative experiences. An integrative framework is proposed that places both directed attention and stress in the larger context of human–environment relationships.

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Introduction

Evidence pointing to the psychological benefits of nature has accumulated at a remarkable rate in a relatively short period of time. Whether a theoretical understanding of these restorative influences has kept pace with the empirical work is, however, less clear. As Hartig and Evans (1993) have pointed out, theory in this area has been dominated by conflicting positions, one emphasizing stress reduction (Ulrich, 1983) and the other concerned with recovery of the capacity to focus attention (Kaplan & Talbot, 1983; Kaplan & Kaplan, 1989). While it might be argued that these positions are hopelessly far apart, Hartig and Evans hold out hope for a synthesis. The purpose of this paper is to propose a way in which such an integration might be achieved.

A synthesis requires first that there be something to synthesize. There must be entities or ideas distinct enough and useful enough to warrant synthesis. One piece of this is simple to achieve; there is no disagreement over the point that stress is a meaningful concept and that stress reduction is aided by natural environment experience. Ulrich *et al.* (1991), however, have questioned the usefulness of the attentional concept in this context, and have suggested that the performance deficits found in research on attentional fatigue can be understood simply as effects of stress.

Given these questions and alternative interpretation, it seems appropriate to begin by focusing on 'directed attention' and its role in the Attention Restoration Theory. Several studies that examine the relationship between the natural environment and restoration are then presented. This lays the groundwork for proposing an integrative framework which focuses on the causal matrix that connects stress and attention. Finally, the paper offers some directions for future research and concludes with a brief analysis of the merits of distinguishing between stress and attentional factors.

Directed attention

An important source for the attention constructs central to Attention Restoration Theory is the work of William James (1892). His 'voluntary attention' concept concerned the kind of attention that went 'against the grain', as it were. It was to be employed when something did not of itself attract attention, but when it was important to attend nonetheless. Thus James emphasized the centrality of effort in the employment of this kind of attention. Certainly the themes of 'voluntary' and 'effort' suggest the functioning of the will, a topic of considerable interest to James. And in fact, by turning to his discussion of will, it is possible to gain still further insight into his thinking on this issue. In exploring

how one can support a weak intention, such as a thought of something one ought to do but finds difficult, James indicated that the only hope was to inhibit all distractions. There was no way, he felt, to strengthen the weak intention itself. The only support one could provide required protecting it from competing thoughts.

While James did not explicitly relate his discussions of the will and of voluntary attention, it is evident that in both cases the central construct is that of focus, of supporting difficult mental activity in the face of potential distraction. Bringing these two Jamesean themes together yields a more general mechanism than either would be separately. It also suggests an interesting and far-reaching hypothesis about the operation of this mechanism, namely that it is inhibitory in nature. Although James did not use the term 'inhibition', a mechanism whose operation depends on the suppression of competing activity must exert an inhibitory influence.

An attentional mechanism that requires effort, that can be brought under voluntary control, and that depends upon inhibition for its operation offers substantial explanatory promise. James' writings suggested this juxtaposition about a century ago; it is remarkable that this potentially powerful theoretical tool has been ignored for so long.

Although James emphasized the role of effort in the voluntary attention concept, he did not address the possibility that this mechanism was susceptible to fatigue. While not having as well developed a concept of attention, the eminent landscape architect Frederick Law Olmsted not only understood the possibility that the capacity to focus might be fatigued, he also recognized the need for urban dwellers to recover this capacity in the context of nature. This was evident both in his approach to the design of parks, and, quite explicitly, in his writing as well (Olmsted, 1865).

More recently, clinical neurologists, working with brain-damaged patients, have identified a remarkably similar mechanism that they refer to as 'directed attention' (Mesulam, 1985). Interestingly, they relate deficits in directed attention to damage to the prefrontal cortex, a portion of the brain that has long been associated with an inhibitory role in mental functioning (Rothbart & Posner, 1985). Since the concern of clinical neurologists is with rehabilitation, their emphasis is less on specific information-processing capabilities than it is on the broader issue of getting along in the world. Thus they have been particularly concerned with the role of directed attention in 'executive functioning', the capability necessary to lead an organized and purposeful life (Lezak, 1982; Stuss & Benson, 1986).

While inspired by James' notion of voluntary attention for some time (e.g. Kaplan, 1973), we have shifted to calling this concept 'directed attention' as it avoids confusions others have had with James' terminology (Kaplan & Kaplan, 1989).

Directed attention fatigue and basic processes. Drawing together these various themes yields a mechanism with the following properties: it requires effort, plays a central role in achieving focus, is under voluntary control (at least some of the time), is susceptible to fatigue, and controls distraction through the use of inhibition. While the coherence and usefulness of this concept may not be immediately obvious, in fact it is quite familiar. What is familiar, however, is not the mechanism itself, but the state of mind that accompanies its fatigue. Any time one has worked intensely on a project and subsequently finds oneself mentally exhausted, one has experienced this unwelcome state. The typical state of mind of students at the end of a semester is a familiar example. In fact, even a thoroughly enjoyable project, if sufficiently intense and sufficiently prolonged, is likely to lead to this same outcome.

More formally, any prolonged mental effort leads to directed attention fatigue. It might seem peculiar that a mechanism so intimately involved with human effectiveness would be so susceptible to fatigue. Yet, in evolutionary perspective, this apparent limitation might have been quite reasonable. To be able to pay attention by choice to one particular thing for a long period of time would make one vulnerable to surprises. Being vigilant, being alert to one's surroundings may have been far more important than the capacity for long and intense concentration. Further, much of what was important to the evolving human—wild animals, danger, caves, blood, to name a few examples—was (and still is) innately fascinating and thus does not require directed attention. It is only in the modern world that the split between the important and the interesting has become extreme. All too often the modern human must exert effort to do the important while resisting distraction from the interesting. Thus the problem of fatigue of directed attention may well be of comparatively recent vintage.

The importance of directed attention. One might wonder just how important directed attention fatigue is. Granted that scholars who need to concentrate for long periods of time might be disadvan-

taged by this limitation. But there remains the question of how significant the fatigue of directed attention would be for people in general. It may seem unlikely that a deficiency one has never even heard of before could play a major role in human thought and human effectiveness. Nonetheless there are theoretical grounds for suspecting that directed attention fatigue can, and often does, have devastating impacts.

Selection. The capacity to solve problems is often viewed as the crowning achievement of the human mind. Even a cursory look at problem-solving reveals the central role of attention. Consider a mature individual approaching a problem. Such an individual has available a remarkable array of capabilities; there is considerable stored knowledge, along with a multiplicity of perceptual possibilities and a vast repertoire of possible actions. Much as these are powerful resources, most of them are irrelevant to the solution of any particular problem. The very richness of possibilities presents a daunting challenge. Solving a problem requires a focus on the tiny portion of one's repertoire that is pertinent to the problem at hand. It is essential to select appropriately from among the knowledge, the possible percepts, and the potential actions. Ironically, the larger the store of possibilities, the more essential is the capacity for selection. In his chapter on Reasoning (where he treated material closely akin to what we would now call problem-solving), James (1892) both emphasized the significance of selection and illustrated it in the same passage: 'To me now, writing these words, emphasis and selection seem to be the essence of the human mind. In other chapters other qualities have seemed, and will again seem, more important parts of psychology' (p. 223).

In routine behavior much of the selectivity comes from associative connections; one looks for the crucial stimulus or performs the suitable action because that solution has become habitual. But in problem-solving, where well-learned connections are often not available, some other means of selectivity is essential. This is precisely the role that has traditionally been assigned to attention (Moray, 1987). In problem-solving, where routine, associatively-based attention can not be counted on, an attentional capacity under voluntary control is particularly important.

Inhibition and affect. Just as following one's well-learned patterns is often inappropriate to the solving of problems, following the uncensored dictates of one's affective system can be equally maladaptive. As Pennebaker (1991) has pointed out, there are many times when inhibiting one's impulses and inclinations is essential. There are times one must inhibit the inclination to flee, or to act without thinking, or to act in socially unacceptable ways. Carrying out actions that are unpleasant but necessary also requires considerable inhibition. Indeed, this function is so basic that Pennebaker has characterized inhibition as 'the linchpin of health', because, like the linchpin of a wagon, it is what holds everything together. An inhibitory capacity that is under voluntary control is thus an indispensable mechanism for behaving appropriately.

Fragility. Directed attention is not, in itself, more important to problem-solving than knowledge or perception or action. Likewise, it is not necessarily the most important component of the system necessary to generate appropriate behavior. But unlike these components, it is fragile. It is susceptible to fatigue, and as such is more likely to be deficient than are the other components. It is, in other words, often the weak link in the chain. And for this reason it may well be a critical resource in problem-solving and in human effectiveness in general.

As one might expect of a mechanism with such pivotal roles, it is central to the smooth and effective operation of basic information processing functions. And as is so often the case with psychological mechanisms, its importance is most readily observed by the consequences of its absence:

Perception. Lacking effective directed attention, an individual becomes highly distractible, resulting in impaired perception of material that is not inherently engrossing.

Thought. Directed attention is necessary for stepping back from the situation one is facing, for pausing to get a larger picture of what is going on. Thus without the aid of directed attention, it is difficult to deal with situations in which the appropriate action is not immediately obvious. It is also hard to plan and to follow a plan. This leaves the individual caught up in the demands of the immediate situation, unable to transcend momentary pressures and temptations.

Action. Inhibition is essential to delay and reflection. Lacking this capability an individual behaves in a less adaptive and appropriate fashion. Without the patience and endurance necessary to carry out difficult or unpleasant tasks, behavior becomes more oriented to the short term. Social

behavior, which also depends upon inhibition, becomes less appropriate. There is also a greater inclination to be impulsive, to take unnecessary risks, and to act in an impatient and hasty manner.

Feeling. Irritability is a hallmark of a person who cannot draw on directed attention. There is an interesting contrast here to stress, which is characterized by anxiety. Anxiety often leads to seeking to be with others; irritability tends to have the opposite effect. Thus it is not surprising that there is evidence suggesting that under these conditions people are far less likely to be willing to help one another (Sherrod & Downs, 1974; Cohen & Spacapan, 1978).

Directed attention is, thus, a key ingredient in human effectiveness. The fatigue of directed attention is similarly a key ingredient in ineffectiveness and human error. Unfortunately, even momentary lapses in directed attention, at critical times, can have dire consequences. Airplane pilots, ship captains and operators of nuclear or chemical plants provide vivid examples, since for each of these roles, at least one major accident has occurred under conditions when directed attention would be predicted to be at a low ebb (Moore-Ede, 1993). In fact, a study of airline crashes when equipment was not at fault found in every instance that there were disruptions of sleep schedules for key personnel (Wolfe, 1992). As the work of Broadbent *et al.* (1982) suggests, a state of mental fatigue may well be at fault in a large percent of those cases in which accidents are attributed to 'human error'.

The Restorative Experience

The restoration of effectiveness is at the mercy of recovery from directed attention fatigue. Sleep provides one approach to recovery. While useful, it is insufficient. Certainly for serious cases of directed attention fatigue, insomnia is likely to set in long before full recovery has taken place. In order to rest directed attention, it is necessary to find some other basis for maintaining one's focus. What is needed is an alternative mode of attending that would render the use of directed attention temporarily unnecessary.

Fortunately there is a way to meet these requirements and, also fortunately, it is widely available. This notion too, like the directed attention concept, derives from James' perceptive analysis of attentional processes. In his discussion, James contrasted voluntary and involuntary attention. The latter is a form of attention that requires no effort. Although James does not deal with this explicitly, it seems reasonable to assume that both types of attention are similar in being inhibitory and in having their effect through suppression of competition. And to venture clearly beyond James' analysis, involuntary attention, requiring no effort, is likely to be resistant to fatigue. Further, while the individual is in involuntary mode, directed attention should be able to rest. Since James' terminology has been confusing for many people and the circumstances that call on the effortless attention are intrinsically compelling, we have substituted the term 'fascination' for 'involuntary attention' (Kaplan, 1995).

There are many sources and types of fascination. Some of these derive from process. For instance, otherwise normal individuals have been reported to rouse themselves out of bed at an early hour in hopes of catching a glimpse of a small, feathered animal whose identity is uncertain. Likewise many are addicted to books in which the identification of the guilty party is difficult but not impossible to predict, and generally is not resolved until the end, even though far more efficient ways to transmit the same information are surely available. Predicting despite uncertainty as practised by gamblers provides another example of process fascination.

Fascination can also come from content. As previously noted, wild animals and caves are among the many contents that do not require directed attention. In some cases extremes of size lend to the fascination of objects or settings. Fascination can also derive from extremes along a 'soft-hard' dimension. Thus, there is the 'hard' fascination of watching auto racing and 'soft' fascination of walking in a natural setting. Soft fascination—characteristic of certain natural settings—has a special advantage in terms of providing an opportunity for reflection, which can further enhance the benefits of recovering from directed attention fatigue (Kaplan, 1993). We have used the concept of 'Restorative experiences' or 'Restorative environments' to refer to such opportunities for reducing the fatigue of directed attention (Kaplan & Kaplan, 1989).

Fascination is thus a central component of a restorative experience. That is not to say, however, that the presence of fascination guarantees that directed attention can rest. Fascination is a necessary, but not sufficient basis for recovering directed attention. It is evident that some researchers have failed to understand that fascination, although important, is but one component of the model.[1] We have, in fact, proposed three additional components

that are integral to our analysis of what makes an environment restorative (Kaplan & Talbot, 1983).

(1) Being away, at least in principle, frees one from mental activity that requires directed attention support to keep going. In fact, people often use 'getting away' as a shorthand for going to a restorative place. But continuing to struggle with the old thoughts in a new setting is unlikely to be restorative. Clearly being away involves a conceptual rather than a physical transformation. A new or different environment, while potentially helpful, is not essential. A change in the direction of one's gaze, or even an old environment viewed in a new way can provide the necessary conceptual shift.

(2) The environment must have extent. It must, in other words, be rich enough and coherent enough so that it constitutes a whole other world. An endless stream of stimuli both fascinating and different from the usual would not qualify as a restorative environment for two reasons. First, lacking extent, it does not qualify as an environment, but merely an unrelated collection of impressions. And second, a restorative environment must be of sufficient scope to engage the mind. It must provide enough to see, experience, and think about so that it takes up a substantial portion of the available room in one's head.

(3) There should be compatibility between the environment and one's purposes and inclinations. In other words, the setting must fit what one is trying to do and what one would like to do.

Compatibility is a two-way street. On the one hand, a compatible environment is one where one's purposes fit what the environment demands. At the same time the environment must provide the information needed to meet one's purposes. Thus in a compatible environment one carries out one's activities smoothly and without struggle. There is no need to second guess or to keep a close eye on one's own behavior. What one does comfortably and naturally is what is appropriate to the setting (Kaplan, 1983).

The relationship of compatibility to one's purposes has several interesting implications. First, one's purposes generally are more readily achieved when one has prompt and useful feedback from the environment. An environment that is compatible will thus be a responsive environment. Second, different people's purposes vary widely. If one's purpose is to be frightened by a horror movie, a snake might be a compatible as well as a fascinating stimulus. Likewise, members of a snake-oriented religious sect might find snakes both fascinating and compatible. For a great many humans, of course, a snake would fail the compatibility criterion. Third, carrying out purposes often involves solving the problems one meets along the way. As we have seen, solving problems involves exercising selectivity, a key function of directed attention. An ambiguous or distracting environment raises many irrelevant possibilities, placing more demand on directed attention. A compatible environment requires less selectivity and hence less directed attention.

A note on cognition

It may be appropriate at this point to address a central misunderstanding of the role of information processing in restoration. Ulrich *et al.* (1991) argue that the compatibility concept is based on cognition, and that cognition is too slow a process to play a role in restoration. There is no doubt that if one defines cognition as conscious, language-based, and dependent upon reasoning, then it will in fact be a relatively slow process. Ulrich *et al.* seem to adhere to such a limited view of cognition.

By contrast, those who consider perception to be a cognitive process—among them James (1892), Bruner (1957), Attneave (1962), Shepard (1975), Hebb (1980), and Margolis (1987)—make none of these assumptions. And perception is, of course, a very rapid process. Another example of rapid cognition is the implicit prediction that people continuously make about what will happen next in the environment (Macphail, 1987). This process is generally unconscious and typically surfaces only when it is falsified by subsequent events. Thus, in an example Hebb has used, one is not aware of making a prediction when picking up a coffee cup at the breakfast table. Should it, however, turn out to contain cold beer, one is suddenly vividly aware of having made a contrary prediction.

Another example is the inference of three dimensions, made from a two dimensional array on the retina. This process is likewise fast and unconscious. There is also no doubt, terminology aside, that rapid, unconscious human information processing occurs in many forms and at many levels of the system.

Nature and the Restorative Environment

An important theme of this paper, namely, the role of the natural environment in human effectiveness, has not been forgotten. We have talked about the significant role that directed attention plays as a component of effectiveness and about the need to

reduce the fatigue of directed attention in order to restore effectiveness. We can turn now to the question of how nature relates to restoration. One approach to this issue is to consider the ways in which natural settings are particularly likely to meet each of the four requirements for a restorative environment. The second approach will be to look to the empirical literature to see what evidence is available.

Revisiting the components of restorative environments

Being away. Natural settings are often the preferred destinations for extended restorative opportunities. The seaside, the mountains, lakes, streams, forests, and meadows are all idyllic places for 'getting away'. Yet for many people in the urban context, the opportunity for getting away to such destinations is not an option. However, the sense of being away does not require that the setting be distant. Natural environments that are easily accessible thus offer an important resource for resting one's directed attention.

Fascination. Nature is certainly well-endowed with fascinating objects, as well as offering many processes that people find engrossing. Many of the fascinations afforded by the natural setting qualify as 'soft' fascinations: clouds, sunsets, snow patterns, the motion of the leaves in the breeze—these readily hold the attention, but in an undramatic fashion. Attending to these patterns is effortless, and they leave ample opportunity for thinking about other things.

Extent. In the distant wilderness, extent comes easily. But extent need not entail large tracts of land. Even a relatively small area can provide a sense of extent. Trails and paths can be designed so that small areas seem much larger. Miniaturization provides another device for providing a feeling of being in a whole different world, though the area is in itself not extensive. Japanese gardens sometimes combine both of these devices in giving the sense of scope as well as connectedness. Extent also functions at a more conceptual level. For example, settings that include historic artifacts can promote a sense of being connected to past eras and past environments and thus to a larger world.

Compatibility. The natural environment is experienced as particularly high in compatibility. It is as if there were a special resonance between the natural setting and human inclinations. For many people, functioning in the natural setting seems to require less effort than functioning in more 'civilized' settings, even though they have much greater familiarity with the latter (Cawte, 1967; Sacks, 1987).

It is interesting to consider the many patterns of relating to the natural setting. There is the predator role (such as hunting and fishing), the locomotion role (hiking, boating), the domestication of the wild role (gardening, caring for pets), the observation of other animals (bird watching, visiting zoos), survival skills (fire building, constructing shelter), and so on. People often approach natural areas with the purposes that these patterns readily fulfill already in mind, thus increasing compatibility.

A nearby, highly accessible natural environment cannot provide the context for all of these goals and purposes. Yet even such a setting is likely to be supportive of the inclinations of those who seek a respite there. Consider the factory worker, racing off during the lunch period, fighting traffic and distractions, in search of a spot in the shade of a tree for a peaceful break. If the peaceful effects were to be worn off totally by the time the return trip is made at the end of the hour, would this ritual be repeated again the next day?

Attention restoration theory and natural environments: empirical findings

Olmsted (1865) was particularly sensitive to the role of 'natural scenery' in restoration: it 'employs the mind without fatigue and yet exercises it; tranquilizes it and yet enlivens it; and thus, through the influence of the mind over the body, gives the effect of refreshing rest and reinvigoration to the whole system' (p. 22). His inspiration, as well as the insights of others with intimate knowledge of the natural setting, were most influential in the development of national parks and in numerous other conservation efforts (Nash, 1968). These early writings relied on personal experience and literary talent. Thoreau's perceptiveness and foresight are perhaps even more appreciated today than in his own time (Anderson, 1968; Stern, 1970).

While such writings have great power and provide deep inspiration for some, scientific evidence is more compelling for others. The empirical literature on nature benefits has been growing steadily (Altman & Wohlwill, 1983; Kaplan & Kaplan, 1989; Francis & Hester, 1990; Relf, 1992). Several studies have addressed the role of nature scenes in holding

attention and interest (e.g. Ulrich, 1979, 1981; as cited by Ulrich & Parsons, 1992).

There are four studies that speak directly to the relation between restorative experiences and information-processing effectiveness, a crucial issue in establishing the distinct role of directed attention. What is particularly striking about these studies is how parallel the results are, despite wide variation in setting and procedure. Several of these studies are clinical- or field-oriented, an important type of research for a theory that is intended to make a difference beyond the laboratory. Such studies bring with them their own set of challenges and limitations of experimental control. The consistency of findings both with respect to each other and with respect to laboratory research is thus particularly useful in establishing the construct validation of the concept.

In the first study, Hartig *et al.* (1991) compared wilderness vacationers with urban vacationers and a non-vacationing control group. Only individuals with backpacking experience and who were engaged in regular physical fitness regimens were included in the study. Following their trip, the wilderness group showed a significant improvement in proof-reading performance, a task that is highly demanding of directed attention. By contrast, the other two groups showed a pre-test-to-post-test decline. Interestingly, the wilderness groups had the lowest overall happiness score at the post-test. At a 3-week follow-up, however, they showed the highest levels of overall happiness.

In the second study, also reported by Hartig *et al.* (1991), participants were randomly assigned to one of three conditions. Those in the 'natural environment' and 'urban environment' conditions drove to field sites where they completed attentionally fatiguing tasks before walking for 40 minutes in the respective setting. Those in the passive relaxation condition completed the same set of tasks before spending a comparable period listening to soft music and reading magazines. The pre-treatment manipulation was intended to ensure attentional fatigue; a check on this manipulation was also included. Hartig *et al.* reported that in this more controlled study, as in the initial quasi-experimental one, those in the nature-setting condition performed better on the proof-reading task. The second study also included self-report evaluations of the 40-minute experience in terms of being away, fascination, coherence (an aspect of extent), and compatibility. These were summarized in a 'perceived restorativeness' score which was, on average, highest for the natural environment group and was positively correlated (r=0·22) with the proof-reading score.

The other two studies used a new measure that was theoretically derived specifically to test the effect of restoration on directed attention. This measure is based on the Necker cube, a wire frame drawing whose perceived orientation in depth appears to reverse over time. Necker cube fluctuation is an individual difference measure of long standing. A common interpretation of the apparent reversals is the satiation of the representation of a given perspective, thus allowing the alternative perspective to dominate (Orbach *et al.*, 1963; Cornwell, 1976). This interpretation suggests a direct parallel to situations requiring directed attention, namely the potential cessation of a given mental activity due to competition from some other mental activity. If this interpretation is correct, then by intentionally focusing on the cube as it appears at a given moment, its apparent change to the other possible orientation should be delayed. In other words, it should be possible to slow the rate of reversals through exertion of directed attention. Further, the more fatigued the directed attention, the less effective such an effort should be. Thus a high 'Necker Cube Pattern Control' score (the degree to which the rate is slowed relative to the individual's base line) should provide an indication of the strength of this inhibitory capacity.

Cimprich's (1992, 1993) clinical study of recovering cancer patients also supported the link between the restorative experience and enhanced effectiveness. Cancer patients are generally instructed in necessary self-care following discharge from the hospital. They frequently have difficulty in remembering such information, thus seriously jeopardizing attaining optimal treatment outcomes and quality of life. It has also been observed that following cancer treatment patients with a clean bill of health from a medical perspective nonetheless experience persistent and diverse coping problems, including difficulties in interpersonal relationships and limitations in returning to former activities.

Feeling that these clinical observations suggested serious problems of directed attention fatigue, Cimprich studied recovering breast cancer patients at four time points during the 3 months after surgery, using a wide range of attentional and other measures. Participants were randomly assigned to either the experimental intervention or usual care control group. The former involved having each person sign a contract agreeing to participate in three restorative activities (of at least 20 minutes each) per week. While the notion of restorative activities

was explained in broad terms with numerous examples, participants in the experimental group generally selected nature-based activities such as walking in nature and gardening to fulfil their contracted time. The control group received no information about the proposed attention-restoring activities until after the study was completed; however, to ensure that they received equal attention, time was spent in discussing the importance of usual self-care activities, such as frequent rest periods and monitoring of untoward symptoms.

Cimprich reported that the participants in both groups showed severe attentional deficits after surgery before the intervention was initiated. The experimental (restorative) group showed significant improvement in attentional performance over the four times they were measured; the control group did not. The Necker Cube Pattern Control measure was particularly sensitive to attentional changes such that the restorative group showed improvement in the capacity to limit pattern reversals, while the control group showed a significant decline in this capacity by the end of the 3-month study period. Mood scores, however, did not show a significant relationship with the measures of attentional capacity.

The intervention also appeared to have an impact on life patterns. In the restorative group, participants went back to work and were more likely to return full time. Another striking difference was the inclination of members of the restorative group to start new projects (such as losing weight, music lessons, and volunteer work). No new projects were reported by the control group participants. And finally, experimental group members showed significantly greater gains on quality of life ratings by the end of the study period.

What is particularly remarkable about this study is the effect of a very modest intervention (three activities of at least 20 minutes a week) on a problem that, according to the literature in the area, can undermine the capacity to deal with and to adjust to the effects of a serious illness such as cancer and its treatment.

Finally, Tennessen, C. & Cimprich, G. (in press) studied the possible restorative benefits of a natural view from a college dormitory window using a battery of attentional and other measures. Dormitory views ranged from all natural to all built views. Controlling for the geographic location of the buildings, undergraduates with more nature in their dormitory view scored significantly higher on the Necker Cube Pattern Control measure and the Symbol Digit Modalities Test. Those with more natural views also tended to rate themselves as functioning more effectively in daily life activities requiring directed attention than those with more built views. The observed differences in attentional performance were not related to age, gender, or year in school. Finally, there were no differences in mood state based on type of dormitory view.

Taken together these studies make it reasonable to suspect that there is a link between the restorative experience and directed attention. Further, the majority of these findings were obtained without corresponding influences on mood. Since mood enhancement is a frequent goal of stress reduction procedures (presumably to reduce the aversiveness of the stress inducing situation), this finding is suggestive of a distinctive effect of restorative experiences on directed attention.

Toward an Integration

It is time to turn to the synthesis of the stress-oriented and the attention-oriented theories of restorative experiences that Hartig and Evans (1993) encouraged. Since the stress-oriented position put forward by Ulrich *et al.* (1991) does not permit a significant role for attention, the challenge can be defined as developing an integrated theory of stress that permits such a role. Ulrich and his colleagues emphasize attentional decline (and performance decline in general) as a consequence of stress. The integration proposed here, which focuses on the various factors that lead to stress, creates a quite different perspective on the role of attentional decline.

The causes of stress

A distinction is often made between physiological and psychological theories of stress (Evans, 1982). The former concerns the autonomic nervous system reaction to harm or to a threat of harm. The latter, following Lazarus (1966), tends to focus on a cognitive appraisal of whether the individual has the resources necessary to deal with a given challenge. Fisher *et al.* (1984, p. 77), however, make the useful point that 'physiological and psychological stress reactions are interrelated, and do not occur alone'. Furthermore, they distinguish between stimuli 'aversive enough in themselves' to evoke a stress response and those requiring more information processing before a stress response occurs. The integration I propose follows the lead of Fisher *et al.* with respect to both these points. It differs in plac-

ing greater emphasis on the factors *leading* to a stress response, and particularly in the central role of resource inadequacy as a causal factor.

Let us begin with the generally accepted notion that the stress response is an organism's adaptive mobilization to deal with a potentially negative situation. The schematic organization of the factors that I propose as leading to this adaptive mobilization, depicted in Table 1, is based on two major categories, harm and resource inadequacy.

Harm can be direct, as when one is injured (either physically or psychologically). Alternatively, it can be signalled by a perceptual pattern. The latter case is in the spirit of Zajonc's (1980) 'preferences need no inferences' theme. In other words, certain patterns, like something suddenly looming in one's face, automatically indicate the threat of impending harm.

'Resource inadequacy', focuses on whether one has the resources necessary to deal with the situation one is facing (or anticipates facing at some point in the future). It is divided into three subcategories. The first, following Lazarus (1966), emphasizes the *appraisal* by which the individual determines that the available resources are insufficient. This implies a deliberative process by which a conclusion is reached.

The second subcategory also involves information processing but of a variety so much faster and so unlikely to be conscious that the term 'appraisal' would not be an appropriate description. Rather 'intuition' or even 'pre-attentive process', following Neisser (1967) would be more appropriate.

An example is provided by the mechanism by which an individual begins the process of making sense out of a scene or visual array. A crucial first step is the segmentation of a scene into 5±2 objects or regions (Lesperance, 1990). This simple but powerful process, which is believed to depend on a primitive brainstem structure (Bruce *et al.*, 1986), is essential to the process of understanding and dealing with the visual environment. As a highly adapted mechanism, it is usually successful. This is not, however, always the case. While some scenes parse readily, others resist attempts to organize them. It is hypothesized that in such cases an immediate sense of discomfort will occur. One is suddenly faced with a situation of potential confusion, a situation in which one cannot be sure one has what it takes to resolve it.

TABLE 1
Factors leading to stress

Harm	Resource inadequacy
Direct	Determined via appraisal
Perceptual pattern or signal	Determined via intuition
	Occurring through gradual depletion

These two types of resource inadequacy mark ends of a continuum. While the degree of consciousness and the speed of processing might seem to be parametric issues not worthy of major theoretical distinctions, it is, as we have seen, at the heart of an unfortunate misunderstanding of the role of information processing in stress and restoration. Ulrich *et al.* (1991) appear to avoid allowing cognition to play a role in the stress process, due to the same misconception that led them to deny the relevance of the (presumably cognitive) compatibility concept in restoration. Once again, definitional issues aside, there is overwhelming evidence that information processing can occur rapidly and without consciousness.

The third type of resource inadequacy involves neither assessment nor appraisal. Rather, it concerns circumstances in which a task, either neutral or even pleasant, gradually draws down some basic resource, leading to a stress reaction. Unlike the other members of this category, where the resource inadequacy is either predicted or anticipated, in this case there is a reaction to the actual depletion of the resource. This type of resource inadequacy is closely akin to that described by Hancock and Warm (1989), which is a central part of their model relating vigilance or sustained attention to stress.

Regardless of the type one is considering, the resource inadequacy category inevitably raises the question of what sort of resources might be involved. Sometimes resources external to the organism such as money or friends in high places are undoubtedly crucial. At other times the physical strength of the individual may be the key resource at issue. But much of the time it is likely that *psychological* resources are the crucial limiting factor. How to conceptualize such resources is, then, our next task.

A possible alternative to consider would be that there are a large number of resources that play this role. One might wonder, for example, if one had the needed empathy to handle a situation, or the needed insight, or the needed patience. The problem with this alternative is that such a list would be endless, and the time required to come to a conclusion would be prohibitive. Thus, on adaptive grounds, it seems more reasonable that there would be some basic underlying resource. This is consistent with people's behavior; when someone states that they just don't have what it takes to deal with

some forthcoming challenge, they speak as if referring to a broad, global concept.

What would the requirements be of such a resource? It would have to be important to the individual's functioning, and pervasive in its influence. It would also have to function like a resource; in other words, it would have to be subject to depletion and to subsequent inadequacy. It is perhaps hardly surprising at this point in the discussion to discover that directed attention fits these requirements remarkably well. Directed attention is important because of the central role of selectivity in human information processing, and because of the significance of inhibition in managing behavior. It is also important for the very reason that it is fragile, that it is susceptible to fatigue. As the weak link in the chain, it is a highly likely cause of incompetent or inappropriate behavior.

A potential drawback in this argument is that attention has only rarely been treated as a resource (Simon, 1978). Furthermore inhibitory attention is rarely discussed, and the fatigue of this mechanism is essentially not considered. Perhaps it is for these reasons that Ulrich *et al.* (1991) favor the 'more mainstream terms' relating to stress. In fact, there is more support than this would imply, although the conflicting uses of the term 'stress' are part of the difficulty. Hancock and Warms (1989) provide an interesting example of this. Attention, which they consider equivalent to 'psychological adaptability', is in fact the key psychological resource in their model. They characterize this attentional resource as being reduced by task demand (which they refer to, following their distinctive terminology, as 'input stress'). The loss of attentional resources in turn elicits a physiological response, which other investigators refer to as stress.[2]

(As Lazarus (1966) pointed out long ago, the original meaning of stress in the engineering context was the force or pressure directed at an object. Selye (1956) reversed the meaning of the term, using it to refer to a reaction to a pressure rather than to the pressure itself. Others, however, including Hancock and Warm, retain the original engineering usage, referring to environmental pressure as 'input stress', or, at times, simply as 'stress'.)

Thus the integration proposed here and the model proposed by Hancock and Warm have several remarkable similarities, despite the fact that the conclusions have been reached by quite different routes. In the model proposed here, as in theirs, insufficient attentional resources will often be an antecedent of stress. The proposed model differs, however, in incorporating anticipated resource insufficiencies and non-resource issues into a framework that attempts to address a broader range of factors that lead to stress.

Implications for research, past and future

While the proposed integration is consistent with much of the theorizing in the stress domain, it is in direct conflict with a particular class of theories. It is important to recognize that theories of stress vary widely, ranging from the modest to the expansive. The latter can become so broad and diffuse as to cover everything and explain nothing.

One of the claims characteristic of the very broad theories of stress is that stress not only has physiological and experiential consequences, but that it has extensive impacts on performance as well. A number of studies have been cited as supporting one aspect or another of this very broad approach. However, one of the contributions of the integration proposed here is to indicate how challenging it is to carry out research that speaks to these issues in an unambiguous fashion. The central difficulty is that under a wide range of circumstances one would expect resource deficiencies and stress responses to occur together. Thus, although the contributions of directed attention and stress are distinct, the frequent co-occurrence could readily lead to the assumption that one concept subsumes the other.

Figure 1 illustrates three patterns that would tend to lead to the joint presence of resource deficiencies and stress responses. In Pattern A resource deficiency is a precursor of stress. In Pattern B, by contrast, stress is not resource-based (e.g. stress associated with pain and injury), but rather leads to resource deficiency. Pattern C includes those many circumstances (including manipulations popular in stress research) that simultaneously cause both stress and resource depletion. An interesting example of this pattern is provided by the work of Pennebaker (1991). He has shown that listening to a description of a traumatic experience is itself stressful. He also points out that people tend to avoid hearing about the traumas of others when they can avoid it. It follows that behaving in a socially (and humanely) appropriate way in such a situation (as opposed to running away) requires inhibitory control. Being stuck in a situation where one is exposed to a depiction of trauma (as occurs in studies such as that of Ulrich *et al.*) would thus be expected to be both fatiguing of the basic attentional resource and stressful at the same time. Comparably, the exhausting task used in the second study reported by Hartig *et al.* (1991) was very prob-

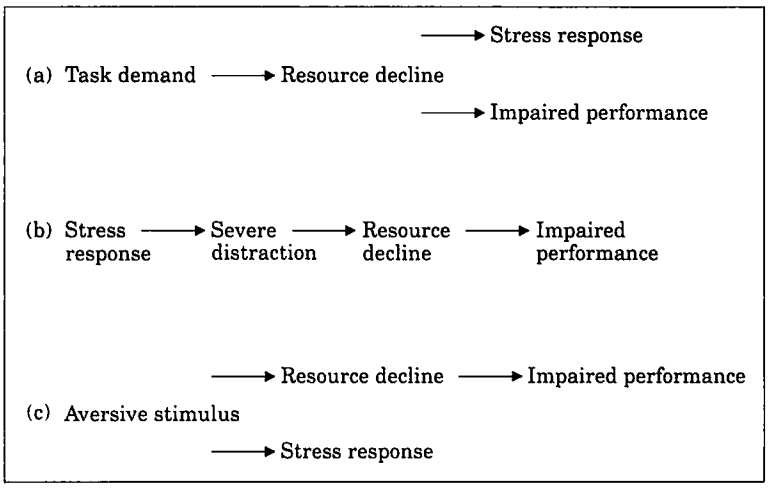


FIGURE 1. Causal linkages associated with impaired performance, illustrating the potential impacts of both the harm and resource inadequacy components of the proposed integration.

ably stressful as well as fatiguing. Clearly the confounding of these variables is a common property of much research in this area which has tended to stand in the way of an understanding of the causal relationships involved.

Given this confounding of stress and attention in so much research, the co-occurrence of stress and performance decline needs to be interpreted with caution. It is inappropriate to jump to the conclusion that stress is the cause of impairment in such cases. Fatigue of attention may well be the causal factor, for the very reason that selectivity and inhibitory control are so central to effective information processing.

The challenge facing research attempting to obtain unambiguous evidence in this area is illustrated by two studies which, although cited as supporting a broad stress theory, are entirely consistent with the expectations of the integrative framework proposed here.

Bohnen *et al.* (1990) studied the impact of continuous mental tasks (accompanied by noise) on stress and performance. Although performance was not impaired for the group as a whole, the participants with higher cortisol reactions (the stress measure used in this study) showed a greater attentional deficit. While the authors prefer the 'stress leads to impaired performance' interpretation, they openly acknowledge that the stress response may be 'a marker for ineffective coping with the demands of continuous tasks', or in other words, an outcome of resource depletion.

Another study suggestive of the effect of resource depletion utilized a pleasant (as rated by participants) learning task at a video display terminal as an independent variable (Lundberg *et al.*, 1993). Several physiological measures of stress were elevated following termination of the task. This study has been cited by proponents of broad stress theory as an example of stress occurring without an aversive stimulus. It would seem, however, that the resource depletion concept allows a more adequate explanation. Even tasks perceived as pleasant by participants can lead in time to resource depletion and ultimately to a stress response.

The fact that resource depletion takes time is part of a larger set of temporal issues that cry out for exploration. Attentional fatigue is slower to develop than is stress. It is also slower to recover. Hartig (1993) found that while stress recovery occurs more rapidly, it also dissipates more rapidly. Recovery from mental fatigue, while a slow process, may also be more durable. Clearly more information on these temporal parameters is urgently needed.

A second set of temporal issues has implications for the design of future studies in this area. As Fig. 1 suggests, a resource decline can lead to stress and a stress response can lead to a resource decline. Thus, even if care is taken to select manipulations that are relatively pure with respect to their impact on either directed attention fatigue or stress, the duration of the manipulation must be carefully chosen to keep the attentional fatigue from becoming stressful or vice versa.

Conclusion

The concept of stress is invoked in common usage under a wide assortment of circumstances. One is

'stressed out' when tired, pressured, anxious, exasperated. Feelings of stress can certainly lead to a sense of ineptitude and to being distraught. There are, however, both practical and theoretical reasons for being more analytic about the diverse situations that are so casually cast as 'stress'. The purpose of this paper has been to propose a framework that distinguishes between the stress-related and the attentional components that lead people to seek and benefit from restorative experiences. To earn its keep, the proposed framework should provide insight into matters not illuminated by previous theory. Here are four examples where this is the case:

(1) It explains how information-processing demands are related to attentional fatigue, and, under certain circumstances, to stress.

(2) It explains how one can enjoy what one is doing, be good at it, and confident of a positive outcome and still be exhausted from it.

(3) It explains why the two classes of experiences, one involving fatigue and the other, stress, can feel so different. Any theory that ignores these profound phenomenological differences is throwing away some important information.

(4) It explains how the same task can be stressful at one time and not at another. An individual already fatigued (experiencing resource inadequacy) could find a challenge overwhelming even though the same individual in a rested state might consider the same challenge to be minor. Individuals coming back from vacation sometimes find that a matter long avoided is experienced as relatively trivial given their rested state of mind.

In summary the proposed integration points to the existence of two distinct, albeit interacting, benefits of restorative experiences. Both of these benefits have an important role in an individual's life. Quite obviously anything that aids in the management of stress is desirable. At the same time, however, directed attention also plays a significant role. It is essential to a coherent life and to the identification and carrying out of worthwhile purposes. Looking back on a life of purpose and productivity, even if one experienced some stress along the way, might well be more satisfying than looking back on a stress-free life in which little was accomplished.

The proposed integration also makes a contribution to a larger theory of how humans relate to their environment. It points to the significant role that directed attention, a key psychological resource, plays in coping with challenges. In this perspective the role that natural environments play is a powerful one. Experience in natural environments can not only help mitigate stress; it can also prevent it through aiding in the recovery of this essential resource.

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Notes

(1) Ulrich *et al.* (1991, p. 206) state, 'However an assessment of the viability of a restoration explanation that emphasizes fascination should also take into account the fact that several scientific studies have shown that settings containing certain types of natural stimuli, such as snakes and spiders, do elicit strong "involuntary" attention or fascination, yet the effects are anything but restorative'. Although previous papers have discussed the four proposed components of a restorative experience, Ulrich and his colleagues have apparently misinterpreted the other three components as alternative sources of fascination.

(2) The Hancock and Warm (1989) model is in fact more complicated than this, depending upon an optimal task demand that can vary '... between extreme values of underload and overload. A zone of comfort is located at the central position of this continuum' (p. 527). Despite this complication, however, their basic model focuses on resource depletion. Task demands tax the individual's attentional resources, ultimately resulting in a stress response.

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Short communication

Why viewing nature is more fascinating and restorative than viewing buildings: A closer look at perceived complexity

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Highlights

- The role of recursive, fractal-like complexity in people's positive responses to natural and built scenes was tested using a psychological approach.
- Participants were exposed to natural and urban scenes, and to magnified parts of these scenes.
- Unmagnified natural scenes were viewed longer and rated as more restorative than unmagnified built scenes.
- Magnified parts of natural scenes were perceived as more complex than magnified parts of built scenes.
- Perceived complexity of magnified scene parts accounted for respectively 47% and 20% of differences in viewing times and in restorative quality between natural and built scenes.

Abstract

The present paper addresses the question which visual features trigger people's often more positive affective responses to natural compared to built scenes. Building on notions about visual complexity and fractal geometry, we propose that perceived complexity of magnified scene parts can predict the greater fascinating and restorative qualities of natural versus built scenes. This prediction was tested in an experiment in which 40 participants viewed and rated 40 images of unspectacular natural and built scenes in their original size, and at 400% and 1600% magnification levels. Results showed that the original, unmagnified natural scenes were viewed longer and rated more restorative than built scenes, and that these differences were statistically mediated by the greater perceived complexity of magnified parts of natural scenes. These findings fit with the idea that fractal-like, recursive complexity is an important visual cue underlying the restorative potential of natural and built environments.

Introduction

Research has consistently shown that interacting with natural environments can improve mood and attention, reduce stress levels, and lead to many other healthy and restorative outcomes (Hartig et al., 2014). Merely viewing trees or plants from a window, or even images of nature can already have measurable positive effects (Grinde and Patil, 2009, Honold et al., 2016, Van den Berg et al., 2003). This suggests that, besides physical factors like the stimulation of exercise and improvement of air quality, psychological mechanisms play an important role in the beneficial effects of nature.

Attention Restoration Theory (ART; Kaplan and Kaplan, 1989, Kaplan, 1995) has described one of the basic psychological mechanisms by which viewing nature my lead to beneficial effects. According to ART, most natural scenes capture attention in a pleasant and effortless manner, allowing the mind to rest and wander freely while the capacity for directing attention is replenished. This gentle capturing of attention has been described as 'soft' fascination, to distinguish it from more hard forms of fascination that capture attention dramatically and cause depletion of executive attentional resources.

The mechanism of soft fascination is widely acknowledged and supported by analyses of people's eye movements when viewing high and low fascination images (Berto et al., 2008). It leaves, however, unanswered the fundamental question which distinctive visual characteristics make viewing natural scenes more fascinating than viewing built scenes (Valtchanov and Ellard, 2015). Finding this missing piece of the puzzle is not only of theoretical importance, but may also contribute to a more effective design of urban green space that makes optimal use of its health-supporting ingredients.

A potential candidate for being that special cue that triggers soft fascination with nature is visual complexity (Berlyne, 1971, Nadal et al., 2010). Natural environments tend to be characterized by intermediate levels of visual complexity, which appear to be just right for attracting attention in a moderate, pleasant way. By contrast, most human-made environments are either highly complex (evoking hard fascination) or virtually lacking in visual complexity and unable to capture attention at all (e.g., Wohlwill, 1983). However, environmental perception studies have revealed that subjective measures of perceived complexity, such as the question "how many different elements are there in this scene", only predict fascination and other positive responses within natural and

built domains. These measures cannot account for differences between these domains (Kaplan et al., 1972, Sparks and Wang, 2014).

A scene's overall level of visual complexity is not only determined by the number and amount of elements, but also by the degree to which visual information is structured and ordered across scale levels (Nadal et al., 2010). This latter, more hidden dimension of visual complexity is not readily perceivable and cannot be assessed with standard subjective measures. To capture the interplay between variety and order, researchers have increasingly used objective measures of visual complexity based on notions of information theory (e.g. Kolmogorov complexity and Shannon entropy) and fractal geometry (Machado et al., 2015, Marin and Leder, 2013). Especially fractal geometry has been found useful in describing the visual complexity of natural environments (Taylor et al., 2011). Fractals capture the order and structure in natural environments by the recurrence of similar visual information across multiple scale levels. This is illustrated by the fact that natural scenes retain roughly the same amount of elements and form as one zooms in and out of the scene.

The fractal dimension is an index of the extent to which a space is filled by details, and as such can be considered a measure of visual complexity (Machado et al., 2015). Research has shown that people respond most positively to fractal images and patterns with an intermediate fractal dimension that is commonly found in nature, which suggests that the visual system might be tuned to the processing of natural information (Aks and Sprott, 1996, Taylor et al., 2011). Furthermore, EEG recorded alpha waves, an indicator of a wakefully relaxed state, tend to be larger for natural (statistical) fractals than for artificial (exact) fractals (Hagerhall et al., 2015). Thus far, however, research on human responses to fractals has exclusively relied on objective methods such as the box-counting technique to measure fractal characteristics. Although such measures are highly informative, they do not capture the more subjective components of environmental perception.

In the present research, we take a more subjective, psychological approach toward assessing recursive, fractal-like complexity. Specifically, we adapted a method described by Mandelbrot (1981), in which an image of an environment is cut into parts, after which the parts are magnified to the same size as the original image. The more elements remain visible in the magnified parts, the higher the environment's fractal complexity. Following this example, we asked participants to rate the perceived complexity of photographs of natural and urban settings, and cropped segments of these photographs at two magnification levels. We also assessed participants' free viewing times of the images as a well-established behavioral measure of fascination (Lang et al., 1993), which has been previously applied in restorative environments research to assess differences in fascination between natural and built settings (Berto, 2005). Furthermore, we obtained self-reports of fascination and other restorative outcomes for the original, unmagnified images.

We had three hypotheses. First, in line with previous restorative environments research, we predicted that unmagnified natural scenes would be viewed longer, and rated as more restorative, than unmagnified built scenes. Second, reflecting the recursive, fractal complexity of nature, we predicted that magnified parts of natural scenes would maintain higher levels of perceived complexity and fascination than magnified parts of built scenes. Third, based on the idea that positive responses to nature are partly triggered by recurring visual information on lower scales that only becomes visible with magnification of scene parts, we predicted that perceived

complexity of magnified scene parts would statistically mediate differences in viewing times and restorative quality between the unmagnified natural and built scenes.

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Section snippets

Stimuli

The stimulus set consisted of 40 photos of everyday, unspectacular scenes in Belgium and The Netherlands. Half of the scenes depicted common natural objects and places such as trees, bushes and grassy spots, the other half depicted residential and office buildings. We selected small-scale setting types instead of more panoramic views to minimize the influence of compositional variables such as mystery or openness, which may influence people's responses to a scene independent of its naturalness. …

Results

Consistent with our first hypothesis, participants spent more than a second longer viewing the unmagnified natural scenes than the unmagnified built scenes, b=1.16, 95% CI=0.45–1.87, and they also rated the unmagnified natural scenes as significantly more restorative, b=1.37, 95% CI=1.12–1.62, ps<0.001. At the same time, participants rated the unmagnified natural scenes about equally complex as their built counterparts, b=0.07, 95% CI=−0.16–0.30, p>0.27. This latter finding implies that the …

Discussion

The present study showed that magnified parts of natural scenes were perceived as more complex than magnified parts of built scenes. Furthermore, differences in perceived complexity of magnified scene parts statistically mediated the greater fascinating and restorative qualities of unmagnified natural versus built scenes, as measured by free viewing times and self-reports. These findings suggest that positive responses to natural scenes at least partly result from bottom-up processing of …

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Form and color visual perception in green exercise: Positive effects on attention, mood, and self-esteem

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Highlights

- Single or combined visual perceptions in green exercise may improve mental health.
- Visual perception of a tree form improved total mood disturbance and self-esteem.
- Visual perception of the color green alone during cycling diminished anger.
- Combined form and green color visual perceptions during cycling improved attention.

Abstract

Physical activity performed in a natural environment, especially among green spaces, is associated with mental health benefits. Yet few studies have explored the separable influences of visual perception on the effects of green exercise. The present study assessed the extent to which two components of visual perception (form and color) contributed to mental health benefits by separating the form and color characteristics of an image of a green tree. In total, 76 healthy college students (18–24 years of age) engaged in incremental cycling exercise at a moderate intensity while

viewing an image in front of them on a large screen. Participants were randomly assigned to one of four groups in which the image they viewed was a green tree, an achromatic tree, a formless color green, or a formless achromatic color. Before and after cycling (test time), participants' selective attention, mood state, and self-esteem were assessed using the Perception and Attention Function battery and the Chinese versions of the Profile of Mood States scale and the Rosenberg Self-Esteem Scale, respectively. Significant interactions detected between test time and form perception indicated that scores in total mood disturbance decreased and scores in the esteem subscale and self-esteem scale increased after cycling while viewing trees. A significant interaction between test time and color perception indicated that anger decreased in the two green color conditions. A significant interaction of color perception by form perception by test time was associated with a significant decrease in response times on the attention task after cycling among participants who viewed the green tree. Our findings are important for interpreting mechanisms underlying characteristics attributable to environmental benefits and revealed that single (color or form) or combined (color and form) visual perception improved the mental health benefits of exercise. These findings may also inform the design and planning of urban green spaces to maximize green exercise effects.

Introduction

Despite an increase in natural environment space or urban green spaces (i.e., community space comprising land, such as parks, rather than buildings) to promote residents' physical activity and public mental health (Byrka & Ryczko, 2018; Das & Gailey, 2022; Tyrväinen et al., 2014), few studies have investigated the mechanisms underlying the specific beneficial characteristics of green exercise. For health purposes, increasingly more urban green spaces are serving as natural environments within which physical activities can take place. Physical activities, such as walking, running, and cycling, in natural environments (i.e., green exercise) have more synergistic benefits than those from exposure to other environments or from engaging in physical activity alone or being in a natural environment alone (Pretty et al., 2005). Green exercise has been widely shown to provide additional benefits to human mental health, including reducing stress (Rogerson et al., 2016) and mood disturbances (Gidlow et al., 2016; Pretty et al., 2007), improving self-esteem (Barton & Pretty, 2010; Pretty et al., 2005), affect (Das & Gailey, 2022), well-being (Rogerson et al., 2020) and enjoyment (Lahart et al., 2019), and restoring attention (Fraser et al., 2019). Landscape planners, designers, and researchers, therefore, should cultivate urban green space for physical activities, to promote physiological and psychological benefits.

Most empirical studies assessing the benefits of outdoor physical activity have focused on the availability, number, or presence of parks and green space (Garrett et al., 2020; Rioux et al., 2016). However, green exercise contributes to greater psychological benefits than exercise in other environments (Barton & Pretty, 2010). Psychological restoration theories, such as the Attention Restoration Theory (ART) and the Stress Reduction Theory (SRT), suggest that compared with non-green exercise, mental health benefits from green exercise are more restorative to public mental health. The ART suggests that restoration from directed attention fatigue contributes to the beneficial effects of green exercise and enables better cognitive function (Jones et al., 2021; R. Kaplan & Kaplan, 1989). The SRT suggests that exposure to nature can reduce stress, arousal, and negative emotions as well as promote recovery through psycho-physiological pathways (Ulrich,

1986; Ulrich et al., 1991). More specifically, people report more positive affect, less negative affect, and improved cognition after exposure to nature (Meidenbauer et al., 2020). In contrast, exposure to urban environments may produce anger and aggressiveness (Hartig et al., 2003). Thus, the restoration of natural environments may extend the mental health benefits of physical activity.

Although exposure to nature has been consistently associated with better mental health, evidence assessing the contributions of the specific characteristics of green exercise that are associated with benefits are scarce. For example, the relationship between street greenery and various health outcomes has been demonstrated (Lu, 2019). This raises an important issue of how to design green spaces in crowded urban areas to meet the demands of physical activity and maximize mental health benefits. In order to better address this issue, it is important to identify which natural attributes confer mental health benefits and to what extent perceptions account for these benefits. However, the specific natural attributes that provide mental health benefits remain unclear.

It has been hypothesized that some sensory perceptions of natural attributes are more important or preferred than others with respect to restoration of mental health (Grahn & Stigsdotter, 2010). Existing evidence has shown that visual perception is incredibly important during exposure to natural environments. Studies exploring the relationship between mental health benefits and visual perception often used images (Pretty et al., 2005) or videos (Rogerson & Barton, 2015). Compared with virtual urban or manufactured environments, visual exposure to real-life nature while participating in physical activities provides more mental health benefits, for example, recovery from stress (Brown et al., 2013) and improved affect (Olafsdottir et al., 2020), self-esteem (Brown et al., 2013), and directed attention (Rogerson & Barton, 2015). By contrast, clear effects on mental health are not observed following the same physical activities performed indoors (Rogerson & Barton, 2015). Such studies have provided preliminary evidence for the beneficial effects of green exercise while visually exposed to nature as well as the significance of visual perception on mental health benefits.

In fact, visual exposure to various natural environments does not always offer the same degree of restorative effects but appears to depend on the natural elements included (Celikors & Wells, 2022; Gatersleben & Andrews, 2013; White et al., 2010). For example, people respond positively to trees (Donovan et al., 2013; Nordh et al., 2011). The presence of trees has been associated with positive mental health, such as recovery (Ulrich, 1984), mood (Chi et al., 2022), well-being (Leather et al., 1998), and lower psychological distress (Zhang et al., 2022). Trees also encourage people to engage in more physical activity (Richardson et al., 2013). These findings suggest that trees may be an important natural element for physical activity and mental health benefits.

Although previous qualitative studies have explored the main traits (e.g., size, shade, color, and leafiness) associated with people's preferred trees (Camacho-Cervantes et al., 2014), there is a need for research that explores how the visual perception of trees in natural environments contributes to the beneficial effects of green exercise. Akers et al. (2012) asked participants to perform moderate-intensity cycling tasks while watching video footage with a high percentage of foliage. The video footage was achromatic-filtered (gray), red-filtered (red), or unedited (green). The results showed lower mood disturbances and perceived exertion with viewing green foliage compared with viewing gray and red foliage. That study provided preliminary evidence that the color green itself may have a contributory effect to the benefits of green exercise. However, there is more than one

visual feature in natural environments, namely, color and form. Thus, improvements in mood states may not critically depend on the color green. Indeed, this has been demonstrated in subsequent studies that failed to find positive effects of perceiving green on mood states (Briki & Majed, 2019). Thus, how visual features affect mental health warrants further investigation.

Therefore, the extent to which two components of visual perception—form and color—contribute to the effects of green exercise was the focus of the present study. Given that green exercise has a wide range of benefits, the present study assessed attention, mood state, and self-esteem as indicators of mental health. As constructivists assumed, the mental health promoting effects of nature are acquired through the semantic idea of nature and its restorative abilities. The recognition and association of features with the concept of nature may influence the preference and restoration of a specific natural environment (Van Hedger et al., 2019). Rich visual features that are more easily associated with the concept of nature may elicit more benefits. Therefore, we hypothesized that cycling while watching images of either the color green or the form of a tree would improve attention, mood state, and self-esteem. The findings of the present study will contribute to a better understanding of the key components of visual perception in green exercise.

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Section snippets

Design

We used a 2×2 between-group experimental study with pretest-posttest design to evaluate the effects of form and color perception on attention, mood state, and self-esteem. The independent variables were color perception (green vs. achromatic) and form perception (tree vs. blank). The dependent variables were attention, mood state, and self-esteem, data for which were collected before and after an incremental cycling exercise performed by participants while they viewed images of a green tree, …

Baseline measurements

As shown in Table 1, there were no significant differences between groups for any baseline measurement (all *p values*>.05), suggesting that any subsequent differences between groups were likely attributable to different form and color perceptions. …

Effects of form perception and color perception on measurements

All measurements obtained from participants after they finished cycling are shown in Table 2. …

Discussion

Although a large body of evidence has shown that green exercise provides mental health benefits across the life span, to the best of our knowledge, few studies have explored which visual perceptions contribute to the green exercise effects. The present study separated critical visual features, including form (trees with wide canopies and short trunks) and color (green), from the natural environment to determine the impact of form and color perception on the effects of green exercise. The …

Conclusion

The present study is, to our knowledge, the first to show that the effects of green exercise on mood and attention grew from single or combined visual perceptions. That is, perception of the tree form improved total mood disturbance and self-esteem, whereas perception of the color green diminished anger, and the perception of form and color together improved attention. Our findings may inform urban green space planning to maximize the benefits of green exercise. …

CRediT authorship contribution statement

Danxuan Zhang: research design, conceptualization, methods, data collection and analysis, writing original draft and modification. **Xinhong Jin:** conceptualization, methods, and draft modification. **Luning Wang:** conceptualization, data collection, and draft modification. **Yahong Jin:** research design, conceptualization, methods, research administration, and draft modification. …

Ethics statement

This study was approved by the Institutional Review Board at Tianjin University of Sport, and was conducted in accordance with the Declaration of Helsinki. Prior to any data collection, all participants were thoroughly informed about the study and provided written informed consent. …

Funding source

This work was sponsored by: the Key Laboratory of Exercise and Health Sciences (Shanghai University of Sport), Ministry of Education Open Fund (2022KF0004); “Chen Guang” project supported by Shanghai Municipal Education Commission and Shanghai Education Development Foundation (21CGA59); Shanghai Pujiang Program (22PJC095). …

Declaration of interest statement

The authors have no conflict of interest to declare. …

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Municipal Education Commission and Shanghai Education Development Foundation (Project Number: 21CGA59) and Shanghai Pujiang Program (Project Number: 22PJC095). We thank all participants for taking part in this study. …

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…Moreover, many papers have also examined mental and physical health outcomes by correlating greenery and their perceptual effects with mental well-being in various contexts (White et al., 2015; Navarrete-Hernandez & Laffan, 2019; Wang, Helbich, et al., 2019; Cheesbrough et al., 2019; Jiang et al., 2020; Zhang, Tan, & Richards, 2021; Shan et al., 2022; Navarrete-Hernandez & Laffan, 2023). Such investigations have extended to its stress relief effects and perceptions in physical activities, such as walking, running, and cycling (Resch et al., 2020; Xiang, Cai, et al., 2021; Huang & Ouyang, 2022; Sun et al., 2022; Brancato et al., 2022; Zhang, Song, & Zhang, 2022; Song, Zhou, et al., 2022; Wang, Lu, et al., 2023; Wang, Liu, et al., 2023; Huang, Tian, & Yuan, 2023; Zhang, Jin, et al., 2023). Spatiotemporal and seasonal variations of greenery's perceived visual quality have also been studied by multiple papers (Eroğlu et al., 2012; Tang & Long, 2019; Verma et al., 2020)….

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…In contrast, passive interactions with such environments showed weaker associations (Holt et al. 2019). Two other studies, which were carried out in China, found a negative correlation between exposure to green spaces on campus and the prevalence of mental health issues among university students (Bai et al. 2024; D. Zhang et al. 2023a). Three studies, one each from Austria (Loder et al. 2020), Malaysia (Malekinezhad et al. 2020), and the Netherlands (van den Bogerd et al. 2018), specifically looked at greenness of the university campus, which was found to have a positive relationships with mental health.…

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...Moreover, green spaces provide residents with opportunities for recreation and tourism. Aesthetics and activities in green spaces have been shown to be effective in promoting the physical and mental health of residents (Coombes et al., 2010; Das and Gailey, 2022; Akpınar, 2021; Zhang et al., 2023). For instance, Deng et al. (2020) have found that nature-related visual and auditory stimuli significantly promote stress recovery....

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Highlights

- Brain activity in posterior midline cortex (PMC) was modulated by color preference.
- Effects occurred when viewing colors but not actively judging color preference.
- Preference did not relate to activity in naming, object or color selective regions.
- The PMC processes subjective value judgements even for basic visual features.

Article preview

Abstract

Introduction

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References (44)

Abstract

Decades of research has established that humans have preferences for some colors (e.g., blue) and a dislike of others (e.g., dark chartreuse), with preference varying systematically with variation in hue (e.g., Hurlbert and Owen, 2015). Here, we used functional MRI to investigate why humans have likes and dislikes for simple patches of color, and to understand the neural basis of preference, aesthetics and value judgements more generally. We looked for correlations of a behavioural measure of color preference with the blood oxygen level-dependent (BOLD) response when participants performed an irrelevant orientation judgement task on colored squares. A whole brain analysis found a significant correlation between BOLD activity and color preference in the posterior midline cortex (PMC), centred on the precuneus but extending into the adjacent posterior cingulate and cuneus. These results demonstrate that brain activity is modulated by

color preference, even when such preferences are irrelevant to the ongoing task the participants are engaged. They also suggest that color preferences automatically influence our processing of the visual world. Interestingly, the effect in the PMC overlaps with regions identified in neuroimaging studies of preference and value judgements of other types of stimuli. Therefore, our findings extends this literature to show that the PMC is related to automatic encoding of subjective value even for basic visual features such as color.

Previous article Next article

Introduction

Over the last century, scientists have provided converging evidence that humans have reliable and systematic preferences for some colors over others (see Hurlbert and Owen, 2015; Palmer et al., 2013, for reviews). Whilst individuals vary in their color preferences, colors such as blue are commonly the most liked and other colors such as yellowy-green the most disliked. In addition, when preferences are plotted against variation in hue, this reveals a systematic hue preference curve which rises steadily as hues get bluer and less yellow, although there is also some interaction with lightness and saturation (e.g., saturated yellow is more commonly liked than dark yellow: Palmer and Schloss, 2010). This pattern of color preference has been relatively stable over time. For example, such preferences were revealed in the earliest studies of color preference dating as far back as the 19th century (Jastrow, 1893 cited in Ling et al., 2006). In addition, although there is some cultural variation in the hue preference curve (e.g., Taylor et al., 2013), the general pattern appears to be consistent across industrialised cultures - some have even claimed that some aspects of color preference are ‘universal’ (Hurlbert and Ling, 2007).

The presence of reliable and systematic color preferences raises the question of why some colors are liked by humans more than others. What is it about color that ‘holds’ affect? (Zajonc, 1980). Potential answers to this question have been provided by behavioural studies that have identified relationships between color preference and various measures such as the ease of naming different colors (e.g., Àlvaro et al., 2015), the valence and number of color-object associations (Palmer and Schloss, 2010; Schloss and Palmer, 2017; Taylor and Franklin, 2012), and the sensory mechanisms of early color encoding (Hurlbert and Ling, 2007). Here we propose that identifying regions of the brain where BOLD activity relates to color preferences will contribute to ongoing debates about color preference, as well as

furthering understanding of the neural basis of human preference, aesthetics and abstract higher level judgements more generally.

There have been a few previous fMRI studies of different aspects of color aesthetics (Ikeda et al., 2015; Johnson et al., 2005; Kim et al., 2012). However, none of these enable us to reliably identify the regions of the brain that are more active when people view colors that they like than those they dislike. For example, the orbitofrontal cortex and amygdala are associated with judgments of color harmony, yet harmony is a process distinct from color preference (Ikeda et al., 2015). Anterior medial prefrontal cortex and the retrosplenial cortex are more active when people make preference judgments compared to similarity judgements about color (Johnson et al., 2005), but it does not necessarily follow that these regions are associated with how much colors are liked. Only one prior study has aimed to identify brain regions where activation on viewing colors is associated with preference for those colors (Kim et al., 2012). However, this study only contrasted activity while viewing a liked color (green) with black: a comparison that is likely to be driven mainly by the difference in lightness. Moreover, the effects are reported at lenient thresholds well below those standardly used in the field. It is therefore impossible to draw firm conclusions from this study.

The current fMRI study aims to identify brain regions associated with color preference: what regions of the brain have stronger activation on viewing a color the more a color is liked? We look for correlations of a behavioural measure of color preference with brain activity when people passively view those colors. Based on two distinct areas of research concerned with, (1) the neural basis of value or aesthetic judgments (e.g., Grueschow et al., 2015; Vessel et al., 2012), and (2) color preference specifically (e.g., Àlvaro et al., 2015; Hurlbert and Ling, 2007; Palmer and Schloss, 2010), we make two sets of predictions.

The first set of predictions is based on prior studies of the neural basis of value and aesthetic judgements (a research area that some have termed ‘neuroaesthetics’, Chatterjee, 2011; Conway and Rehding, 2013). Prior neuroimaging studies of judgements of the beauty of stimuli such as faces (Chatterjee et al., 2009), music (Ishizu and Zeki, 2011) or art (e.g., Vessel et al., 2012), have implicated a number of regions, particularly those included in the brain's so-called default mode network (DMN; Raichle et al., 2001). Of these, the orbitofrontal cortex in particular, has been identified in several studies and suggested to be the ‘beauty centre’ of the brain (Ishizu & Zeki, 2011, 2013). However, there has been debate about the extent to which this region is activated by the actual act of making a judgement of beauty or value rather than being related to these implicitly or automatically

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literature on subjective value judgments (how much is this stimulus valued by you?) has suggested that another hub of the DMN, the posterior midline cortex (PMC, including the posterior cingulate cortex and precuneus), underlies automatic subjective value when value judgments about the stimuli are not explicitly being made (Grueschow et al., 2015).

The second set of predictions is based on the identified relationships between color preference and color naming (Àlvaro et al., 2015), color-object associations (e.g., Palmer and Schloss, 2010) and the sensory mechanisms of color vision (Hurlbert and Ling, 2007). To test both sets of predictions, we first perform a whole-brain analysis of the correlation between the blood oxygen level-dependent (BOLD) response and color preference ratings. To more specifically address the potential relationships identified in the second set of predictions, we identify regions of interest (ROIs) using localisers for color naming, object perception (Grill-Spector et al., 2001), and color selective regions of visual cortex (Lafer-Sousa and Conway, 2013). We then test for predicted associations between BOLD activity and color preference within these ROIs.

In the current study, participants are scanned while they passively view colors and are engaged in a task unrelated to the colors. We correlate BOLD activity with a behavioural measure of color preference taken at the end of the experiment. In this way, we aim to identify the regions of the brain related to implicit and automatic color preferences rather than the actual process of judging preference. If we identify regions also implicated in judgements of value or beauty in prior work (e.g., Chatterjee, 2011), this would provide evidence that these regions are also related to implicit judgments, and that the involvement of these regions extends to color. Effects in PMC would suggest that these regions underpin the computation of automatic subjective value across stimulus domains and different types of value.

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Subjects

Twenty-one healthy right-handed volunteers (11 males; 10 females; mean age: 26 ± 4.4 years) participated. All were native English speakers, had normal or corrected-to-normal vision, and were screened for color vision deficiencies (Red-Green, Ishihara, 1983; Tritan, City 2 nd Ed, Fletcher, 1980). Each participant gave written informed consent and the study was approved by the Research Governance and Ethics committee of the Brighton and Sussex Medical School and the European Research Council …

Color preference curves

Fig. 1-D shows color preference plotted as a function of hue. The most preferred colors include saturated blues and greens and the least preferred include dark yellow and dark orange. Individual measures of color preference were reliable and consistent: preference ratings showed significant correlations between the first and second time each color was rated for each individual (average $r = 0.78$). All individual correlations were positive and significant at $p < 0.005$. …

Whole brain analysis of color preference

In order to determine the …

Discussion

The current study aimed to identify brain regions associated with color preference, by correlating BOLD activity when people passively view colors with their color preferences measured after the scan. We had two sets of predictions: one set which was based on prior neuroimaging studies of value and aesthetics for stimuli other than color (e.g., Grueschow et al. (2015); Vessel et al., 2012, and another set based on previously established behavioural relationships of color preference with color …

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> …Gray, mostly perceived as a neutral color, has been found to minimize concentration (Dalke et al., 2006). Visual neuroscience has revealed the biological foundation for associating color preference with activity in the posterior midline cortex (PMC) regions (Racey et al., 2019). While such associations vary by individual and culture, people commonly like some bright colors (e.g., blue) but dislike certain dark colors (Jalil et al., 2012)….

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Research Paper

Health effects of a forest environment on natural killer cells in humans: an observational pilot study

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Keywords: natural killer cells; activating NK cells; forest trip; forest environment; urban environment

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ABSTRACT

Health effect assessments based on natural killer (NK) cells are an important emerging area of human health. We recruited 90 forest staff members in Xitou, Taiwan and 110 urban staff members in Taipei to investigate the health effects of forest environment exposure on NK cells ($CD3^-/CD56^+$) and activating NK cells ($CD3^-/CD56^+/CD69^+$) in humans. We also invited 11 middle-aged volunteers in a pilot study to participate in a five-day/four-night forest trip to Xitou forest to investigate the health effects of a forest trip on NK cells and activating NK cells. Results showed that NK cells were higher in the forest group (19.5 ± 9.1%) than in the urban group (16.4 ± 8.4%). In particular, the percentage of NK cells was significantly higher in the forest group than in the urban group among the subgroups of male, a higher body mass index (≥ 25 kg/m²), without hypertension, lower high-sensitivity C-reactive protein, hyperglycemia, without smoking habit, and with tea drinking habit. After the five-day trip in Xitou forest, the percentage of activating NK cells of the invited participants from Taipei increased significantly after the trip to Xitou forest (0.83 ± 0.39% vs. 1.72 ± 0.1%). The percentage of activating NK cells was 1.13 ± 0.43%, which was higher than the baseline value of 0.77 ± 0.38% before the forest trip among the seven subjects who participated in the follow-up study four days after returning to Taipei. This study suggests that exposure to forest environments might enhance the immune response of NK cells and activating NK cells in humans.

INTRODUCTION

Natural killer (NK) cells are a subset of lymphocytes with a distinct morphology and the ability to directly kill certain target cells via one or more cytolytic mechanisms. They are important in the human endocrine and immune systems to induce tumor or virus-infected targeted cell death [1, 2]. Activating NK cells produce anti-cancer proteins, such as perforin and granzyme, in host anti-cancer defense mechanisms, where the targeting of cancer cells is known to be of critical importance [2]. Among the cytolytic effector lymphocytes in the innate immune system, NK cells are especially critical for immune surveillance of tumors [2–4]. Studies have shown that immunosuppression is common after standard anti-cancer treatments and that NK cells are particularly suppressed. For example, peripheral blood natural cytotoxicity is diminished significantly in breast cancer patients [3–5].

Human immune systems are highly diverse and not completely understood at present, but recent studies indicate that environmental and non-heritable factors make much larger contributions than heritable factors [6, 7]. Considerable evidence indicates that forest environments can enhance the percentage and function of NK cells and intracellular anti-cancer proteins in lymphocytes [8–12]. Thus, exposure to a forest environment can have health-promoting effects.

Forest environments may have some positive health effects on physiological and psychological activities. In particular, the beneficial physiological health effects of a forest environment enhance immune functions, including human NK cells [8–10], decrease sympathetic nerve activity, enhance parasympathetic nerve activity, and lower blood pressure, pulse rate, heart rate variability, and cholesterol concentration [13–20]. Forest environments are more greatly associated with positive health effects on subclinical cardiovascular disease and health-related quality of life compared with urban environments [21]. Exposure to a forest environment significantly suppressed sympathetic activity and increased parasympathetic activity in young Japanese male adults who participated in a three-day/two-night field experiment compared with an urban environment according to a heart rate variability analysis [14]. Phytoncides from wood essential oils, such as α-pinene and limonene, have been shown to induce human NK cells, as well as the expression levels of perforin, granzyme A, and granulysin [22]. Studies have reported that a forest trip enhanced human NK cells and intracellular anti-cancer protein levels in lymphocytes; moreover, the increased NK cell activity lasted for more than seven days after the forest trip [8–11]. However, these previous studies investigated only the experimental effects of a short-term forest trip on human NK cells. More studies are required to evaluate the health effects of exposure to a forest environment on human NK cells.

The objectives of this pilot study were the following: (1) to determine the percentage of NK cells ($CD3^-/CD56^+$) and activating NK cells ($CD3^-/CD56^+/CD69^+$) in people who live in a forest environment compared with those who live in an urban environment; and (2) to determine the health effects of a forest trip on NK cells and activating NK cells in participants who stayed for five days and four nights in a forest environment.

RESULTS

The mean ages in the urban and forest groups were 44.8 and 45.2 years, respectively (Table 1). The forest group contained more male participants (66.7%) than the urban group (53.6%). The systolic and diastolic blood pressure readings in the forest group were higher (130.3 and 83.2 mmHg, respectively) than in the urban group. Lifestyle habits in terms of alcohol consumption, smoking, coffee, and tea differed significantly among the two groups. In particular, habitual tea drinking was higher in the forest group (87.8%) than in the urban group (62.7%). However, habitual coffee consumption was higher in the urban group (70.9%) than in the forest group (53.3%).

The mean environmental monitoring results are presented in Table 2, including air pollutants, temperature, and relative humidity. The SO_2, NO, NO_2, NO_x, CO, and temperature levels were significantly lower in the forest environment compared with those in Taipei (indoors and outdoors). However, the levels of O_3 and relative humidity were higher in Xitou than those in Taipei. The complete blood cell counts are presented in Table 3. The red blood cell, hemoglobin, hematocrit, and white blood cell counts (e.g., lymphocyte and monocyte) were significantly higher in the forest group than those in the urban group.

Table 4 shows that the percentage of NK cells was positively correlated with male, age, systolic and diastolic blood pressure, high-sensitivity C-reactive protein, and fasting glucose levels. However, the percentage of activating NK cells was not correlated with all cardiovascular characteristics.

Table 5 shows that the percentage of NK cells was higher in the forest group (19.5 ± 9.1%) than in the urban group (16.4 ± 8.4%). After adjusting for age and gender, the regression estimates indicated that the percentage of NK cells, but not activating NK cells, were significantly higher in the forest group than in the urban group. Subgroup analyses for NK cells differences between two groups are also shown in Table 5. The percentage of NK cells was significantly higher in the forest group than in the urban group among subgroups of male, higher BMI (≥ 25 kg/m^2), without hypertension, lower hs-CRP levels, hyperglycemia (fasting glucose ≥ 100 mg/dL), without smoking habit, and with tea drinking habit. However, all subgroups did not differ significantly in terms of the percentage of activating NK cells between the two groups.

Table 6 shows that among the 11 participants, 27.3% were male and the average age was 60.4 years. The participants from Taipei were invited to attend a forest trip (five-day/four-night) to the Xitou Nature Education Area from January 6 to 10, 2014. No event of skin wound or bee bites was reported by the participants during the forest trip. Compared with the measurements obtained in Taipei one day before the forest trip, the percentage of activating NK cells increased significantly among the 11 participants after the forest trip ($p = 0.002$). However, no significant difference in their percentage of NK cells was observed after the forest trip, as shown in Table 6A. Although the percentage of activating NK cells in the participants decreased after the participants left the forest, the forest trip significantly increased the percentage of activating NK cells compared with pre-forest trip levels. This change lasted for at least four days, as shown in Table 6B. The percentage of activating NK cells was 1.13 ± 0.43%, which was higher than the baseline value of 0.77 ± 0.38% before the forest trip among the seven subjects who completed in the follow-up study.

Table 1: General characteristics of staff members living in urban and forest environments

	Environment		
	Urban	Forest	
	N = 110	*N* = 90	*p*-value[d]
Age (year)	44.8 ± 6.6	45.2 ± 10.6	0.704
Male sex (%)	53.64	66.67	0.062
Body mass index (kg/m^2)	23.8 ± 3.48	24.59 ± 3.54	0.113
Waist (cm)	81.52 ± 9.61	84.15 ± 8.80	0.049
Systolic blood pressure (mmHg)	125.06 ± 14.01	130.34 ± 15.28	0.012
Diastolic blood pressure (mmHg)	80.07 ± 10.75	83.19 ± 10.17	0.039
Hypertension (%)	26.36	24.44	0.757
Hypertension with medication (%)	9.09	10.0	0.827
Fasting glucose (mg/dL)	85.83 ± 9.28	91.60 ± 10.92	< .001
Cholesterol (mg/dL)	188.84 ± 35.25	191.87 ± 38.69	0.563
Triglycerides (mg/dL)	106.40 ± 52.21	122.34 ± 85.22	0.123
HDL-cholesterol (mg/dL)	56.57 ± 14.65	54.81 ± 11.78	0.347
LDL-cholesterol (mg/dL)	113.08 ± 30.19	118.30 ± 34.71	0.257
hs-CRP (mg/dL)	0.14 ± 0.18	0.21 ± 0.45	0.169
Alcohol drinking [a] (%)	18.18	36.67	0.003
Smoking habit [b] (%)	20.91	34.44	0.032
Exercise habit [c] (%)	54.72	59.55	0.497
Coffee (%)	70.91	53.33	0.010
Tea (%)	62.73	87.78	< .001

HDL and LDL cholesterol: high-density and low-density lipoprotein cholesterol; hs-CRP: high-sensitivity C-reactive protein; [a]drinking habit: drinking alcohol once or more per week; [b]smoking habit: current smoker and ex-smoker; [c]exercise habit: three times with at least 30 min each per week; [d]Continuous variables were expressed as mean ± SD, and *t*-test was used to perform comparisons.

DISCUSSION

This study is the first to demonstrate the health effects of a forest environment on human NK cells by comparing subjects who live in a forest environment with those who live in an urban environment. The effects were more significant in subjects of overweight, male, and with hyperglycemia. This finding indicates that the immune response of people with specific cardiovascular risk factors may be improved by living in a forest environment. In this study, we further demonstrated the health effects of a forest trip on immune function in terms of activating NK cells. For health effects of a forest environment on natural killer cells, studies in which 13 healthy nurses and 12 healthy males took a three-day/two-night forest trip showed that the increased NK cell activation could last for more than seven days after the forest trip [9, 10]. Our finding is consistent with Li's finding [9, 10] that a forest trip can enhance immune response in terms of activating NK cells and the effects can last for more than four days.

Maintaining enough NK cells is essential for healthy aging. In general, the NK cells increased with age [23]. Our results showed that study subjects in the forest trip group had a higher NK cell percentage than the forest and urban groups, which might be due to the older age of the subjects of the forest trip group than the other two groups (60 vs. 45 years). NK cells ($CD56^+$) are divided into $CD56^{bright}$ and $CD56^{dim}$ major subsets that have both different receptor profiles and functions [24]. Lutz et al. [25] reported that NK ($CD56^{bright}$) cells proliferated rapidly but died relatively slowly. Aging has differential effects on NK ($CD56^{bright}$) and NK ($CD56^{dim}$) cell subsets. Older individuals presented with a significantly higher percentage of NK ($CD56^{dim}$) cells but a significantly lower proportion of NK ($CD56^{bright}$) cells, thus resulting in an increased NK ($CD56^{dim}$) to NK ($CD56^{bright}$) ratio [25, 26]. The age-related increase in the NK cell percentage in older adults may be the result of an accumulation of long-lived NK cells [27].

NK cells are important in the human endocrine and immune systems as first-line effectors to induce tumor or virus-infected targeted cell death [1–2]. Activating NK cells have the ability to directly kill certain target cells. Many studies have demonstrated that NK cell subset distribution and the change in the expression of early activation antigen, $CD3^-/CD56^+/CD69^+$ NK cells

Table 2: Comparisons of the air quality and meteorological data in the forest and urban environments

	Forest	Urban		P_1 value	P_2 value
	[a]*N* = 96	Indoor *N* = 94	outdoor *N* = 96		
SO_2 (ppb)	0.45 ± 0.46	0.17 ± 0.18	3.04 ± 1.43	< .001	< .001
NO (ppb)	0.27 ± 0.24	39.22 ± 22.97	12.45 ± 11.6	< .001	< .001
NO_2 (ppb)	2.61 ± 2.19	4.45 ± 1.61	30.34 ± 9.02	< .001	< .001
NO_x (ppb)	2.44 ± 2.17	43.67 ± 22.14	42.79 ± 18.4	< .001	< .001
CO (ppm)	0.37 ± 0.19	1.09 ± 0.51	0.87 ± 0.31	< .001	< .001
O_3 (ppb)	27.48 ± 16.15	6.65 ± 0.73	13.56 ± 10.4	< .001	< .001
Temperature (°C)	13.05 ± 1.91	17.94 ± 1.03	17.35 ± 1.69	< .001	< .001
Relative humidity	91.36 ± 5.60	67.86 ± 2.86	82.33 ± 6.45	< .001	< .001

P_1 value corresponds to *t*-test comparisons of the Xitou and urban sites (indoor). P_2 value corresponds to *t*-test comparisons of the Xitou and Wanhua sites (outdoor) of the Environmental Protection Agency, Taipei, Taiwan. [a]*N* corresponds to the sample size for the hourly average data.

with respect to clinical response [5, 28–30]. Although the activating NK cells have been established to have the ability to attack the target cells, we still have to actually carry out the activity assay of killing target cells for understanding NK cell activity. In general, NK cell activity was assayed according to the standard microtiter ^{51}Cr-release assay [28, 31]. Consistent evidence from both epidemiological and experimental studies have demonstrated that alcohol consumption [32–33], physical exercise [34], circadian variation [35], menstruation [36], cancer [37–38], age [26, 39], smoking habits [40–41], and environment [10] can affect NK cell activity in human. Furthermore, many studies have demonstrated that a forest environment can enhance the immune response as measured by NK cell activity, and the percentage and absolute numbers of NK cells [8–10].

NK cells in humans are dependent on environmental factors, alcohol consumption, physical exercise, circadian variation, and food [28, 31, 35, 42–43]. Previous studies also suggest that exposure to phytoncides and decreased stress hormone levels may have partially contributed to the increases in human NK cells after the forest trip. In particular, both the environmental factors related to the forest and cardiovascular characteristics were the major factors that affected human NK cells. The specific features of the Xitou forest comprise the biogenic volatile organic compounds emitted by the leaves of *Cryptomeria japonica* trees, including phytoncides such as α-pinene, limonene, and cedrol [44]. A previous study in Japan showed that subjects with healthy lifestyles, such as nonsmokers and those who exercised regularly, had significantly higher NK cells and more perforin, granulysin, and granzyme A/B-expressing cells than subjects with poor lifestyles [45]. Effects of phytoncides from wood essential oils significantly increased NK cell, and perforin, granulysin, and granzyme A/B-expressing cells, whereas they significantly decreased the percentage of T cells, thereby indicating that phytoncide exposure may affect human immune function [46].

We also measured the phytoncides and negative ions during outdoor monitoring of forest and urban environments and indoor monitoring of a wooden house made of Western red cedar (*Thuja plicata*) during the forest trip (Supplementary Tables 1 and 2). We detected several phytoncides such as α-pinene, limonene, and (1R)-(-)-Myrtenol in the outdoor forest fields and α-pinene, limonene, (1R)-(-)-Myrtenol, camphor, and β-caryophllene in the indoor wood house. Studies suggested that phytoncides may partially contribute to the enhanced activating NK cells during the forest trip [8–11]. Our study also demonstrated that most cardiovascular characteristics (age, male gender, SBP, and triglyceride, hs-CRP, fasting glucose levels, and smoking and tea drinking habits) affected NK cell percentage, thereby indicating the potentially confounding factors of NK cell measurements.

Furthermore, we detected significantly lower concentrations of gaseous air pollutants, such as NO, NO_2, NO_x, SO_2, and CO, in the forest environment compared with the urban environment during the study period. Thus, the beneficial effects on immune function suggest a potential link between the better air quality in the forest environment and human health. Ambient air pollution can affect child and perinatal health on immune function by low-dose insults as compared with adult health [47–50]. Exposure to air pollutant toxicity may cause immunosuppression and result in increased expression of aberrant immune responses [47].

The strength of this study was the consistent detection of health effects in terms of increased percentage of NK cells in the observation study among workers living in forest environment and activating NK cells among middle-aged adults who went on the short-term forest trip. The results of air quality monitoring

Table 3: Comparisons of complete blood cell counts for the urban and forest groups

	Urban $N = 110$	Forest $N = 90$	p-value[a]
Red blood cell (10^6/μL)	4.97 ± 0.61	5.18 ± 0.60	0.014
Hemoglobin (g/dL)	14.18 ± 1.83	15.03 ± 1.57	0.001
Hematocrit (%)	42.4 ± 4.48	44.19 ± 3.89	0.003
White blood cell (10^3/μL)	5.76 ± 1.43	6.29 ± 1.54	0.013
Neutrophil (10^3/μL)	3.36 ± 1.05	3.63 ± 1.20	0.093
Lymphocyte (10^3/μL)	1.93 ± 0.56	2.10 ± 0.59	0.034
Monocyte (10^3/μL)	0.30 ± 0.11	0.35 ± 0.11	0.005
Eosinophil (10^3/μL)	0.13 ± 0.10	0.16 ± 0.11	0.066
Basophil (10^3/μL)	0.03 ± 0.02	0.03 ± 0.02	0.439
Platelet (10^3/μL)	258.17 ± 51.62	251.48 ± 47.41	0.345

[a]Continuous variables were expressed as mean ± SD, and t-tests were used to perform comparisons.

in Xitou forest are better than those in Taipei in this study and our previous study [21]. However, this study has several limitations. First, the differences in NK cell percentage between the two groups are associated with the cardiovascular characteristics of participants, such as hypertension status, hs-CRP levels, male, hyperglycemia, and being overweight. Thus, the results may overestimate the difference between two groups. However, controlling all confounding factors would result in over-adjustment. These factors may have attenuated the health effects of the forest environment on the percentage of NK cells. Second, although our study indicated the health effects of a forest trip on activating NK cells, we could not infer that the actual benefits were due to phytoncides in Xitou forest. The specific health effects of biogenic volatile organic compounds from tree leaves in forest environments were not investigated during this study, however the real measurements of phytoncides in the major tree of Xitou forest have been demonstrated in this study site [44]. Third, we did not compare the same study group in the urban trip with the group who went on the forest trip in terms of the percentage of NK cells and activating NK cells. Fourth, the sample size of the forest trip group is relatively small, which may cause the results to be overestimated or underestimated. Fifth, the small difference in the percentage of NK cells and activation NK cells cannot provide strong evidence that will allow us to infer the beneficial effects of exposure to a forest environment.

In conclusion, this study suggests that exposure to forest environments might enhance the immune response of NK cells and activating NK cells in humans. The health effects of a forest environment are important areas of research. Further studies are anticipated to understand the mechanisms that mediate the health effects of forest environments. Such studies should consider not only the phenomenological observations but also the potential influencing factors of NK cells and activating NK cells in humans.

MATERIALS AND METHODS

Study design and population

The study design aimed to determine the health effects on NK cells among staff members who live in a forest environment compared with those of who live in an urban environment. We recruited 90 staff members who live in the forest and 110 urban staff members who live in Taipei for an observational pilot study, which was conducted in the forest or urban environment for more than one year (Supplementary Figure 1). All participants provided informed consent before being subjected to cardiovascular health and biochemical examinations and NK cell measurements. The health examinations of forest participants were conducted from January 6 to 10, 2014 in Xitou, NTU Experimental Forest, Nantou County, and from January 14 to 17, 2014 for urban participants in Taipei.

To demonstrate the health effects of a forest trip on middle-aged subjects, we recruited 15 middle-aged volunteers who had been living in Taipei for more than one year in a small pilot study (Supplementary Figure 2). Subjects with clinical diabetes, major diseases, and documented cardiovascular diseases were excluded. All participants had to undergo cardiovascular health and biochemical examinations, and their NK cells had to be measured before the forest trip. A total of 11 participants with a mean age of 60.4 years were selected. To prevent interference by dietary habits, each subject had to be subjected to dietary control (limited dietary fat and calorie intake according to the National Cholesterol Education Program Step 1 diet) [51] for at least 10 days before leaving for Xitou forest.

These 11 subjects joined a five-day/four-night forest trip in Xitou Experimental Forest from January 6 to 10, 2014. During the forest trip, all participants had to maintain dietary control and walking exercise. On the first

Table 4: Correlation coefficients between NK cell, activating NK cell, and cardiovascular characteristics among staff members living in urban and forest environments ($N = 200$)

	NK cell		Activating NK cell	
	Correlation coefficient	*P*-value	Correlation coefficient	*P*-value
Male	0.192	0.007	0.056	0.428
Age	0.260	< .001	–0.011	0.879
Body mass index	0.073	0.308	0.128	0.072
Systolic blood pressure	0.315	< .001	0.056	0.435
Diastolic blood pressure	0.353	< .001	0.081	0.256
Triglycerides	0.135	0.057	0.062	0.385
Cholesterol	0.123	0.083	–0.092	0.194
High-sensitivity C-reactive protein	0.144	0.042	0.034	0.631
Fasting glucose	0.174	0.014	–0.051	0.475
Smoking	0.057	0.424	0.054	0.450
Alcohol	0.126	0.075	–0.038	0.594
Coffee	–0.136	0.056	0.049	0.487
Tea	0.064	0.366	0.027	0.697

day, the participants walked for 1.5 hours (approximately 1.8 km) in the afternoon in a forest field and then stayed in a wooden house in the forest. In the next three days, the participants walked in two different forest fields for 1.5 hours in the morning and afternoon, respectively. On the fifth day, after their blood was drawn and a health examination was completed, all participants finished the forest trip and returned to Taipei. We took blood samples prior to the forest trip as a control sample on January 3. Overnight fasting blood was also sampled for each participant on the final day (January 10, 2014) of the forest trip and on the fourth day (January 14, 2014) after the forest trip. All blood samples were obtained at 9:00 a.m. on the study day and were placed in an ice/water box at 4°C. Assays were performed within four hours from the blood being drawn to measure the white blood cell counts, percentage of activating NK cells, and proportions of NK cells in peripheral blood. To prevent the potential bias of NK cells due to skin injury or bee bites during the forest trip, every participant had to record any skin injury or bee bites if they occurred.

This study was approved on the thirty-seventh meeting (January 30, 2013) of the Research Ethics Committee of the NTU Hospital. All participants provided their written informed consent before receiving a series of detailed examinations and questionnaires.

Site descriptions of the forest and urban environments

The NTU Experimental Forest in Xitou and the interior office of a commercial building in Taipei served as the forest and urban environment sites, respectively. The Xitou Experimental Forest covers approximately 2,349 ha and is mainly a natural hardwood forest with some plantations that predominantly contain conifers. The annual rainfall was 2,590 mm between 1941 and 2010, where 80% of the rainfall occurred between May and September. The mean relative humidity and temperature from 2011 to 2015 were 88% and 18°C, respectively, according to the Xitou monitoring station of the NTU Experimental Forest. Our environmental monitoring site was located at an elevation of 1150 m near the meteorological station (23°40N 120°47E) of Xitou Experimental Forest. The commercial building was a financial building located near the Taipei main station in Taipei. Our study subjects worked for a financial securities corporation. Interior office air quality monitoring was conducted on the twenty-first floors of the commercial building. The mean relative humidity and temperature were 73% and 24°C, respectively, according to the Taipei monitoring station of the Central Weather Bureau [52].

Exposure assessments

The instruments were set up in the Xitou Experimental Forest and in the interior office of the commercial building (indoor environment) in Taipei. The monitoring system was composed of a nitrogen oxide (NO_x) analyzer (Model CLD 88YP, ECO Physics, Switzerland), a sulfur dioxide (SO_2) analyzer (Model 43i-TLE, Thermo Scientific Inc., USA), a carbon monoxide (CO) analyzer (Model 48i-TLE, Thermo Scientific Inc., USA), an ozone (O_3) analyzer (Model 49i, Thermo Scientific Inc., USA), and a temperature and relative humidity probe (Metone 083C, Met One Inc.,

Table 5: Comparisons of NK cell and activating NK cell between staff members living in urban and forest environments

		NK cell (%)			Activating NK cell (%)		
	N	Urban *N* = 110	Forest *N* = 90	*P* value	Urban *N* = 110	Forest *N* = 90	*P* value
Crude value		16.4 ± 8.4	19.5 ± 9.1	0.01	1.81 ± 2.85	1.55 ± 1.14	0.37
Adjusted value[a]		16.7 ± 0.8	19.2 ± 0.9	0.03	1.83 ± 0.22	1.53 ± 0.24	0.35
Age, years							
< 50	143	15.9 ± 7.7	17.4 ± 8.1	0.27	1.96 ± 3.17	1.5 ± 1.03	0.22
≥ 50	57	18.4 ± 10.7	23.0 ± 9.7	0.10	1.28 ± 0.73	1.63 ± 1.31	0.21
Gender							
Female	81	15.2 ± 8.5	16.7 ± 8.3	0.44	1.52 ± 2.47	1.57 ± 1.51	0.91
Male	119	17.5 ± 8.3	20.9 ± 9.2	0.04	2.07 ± 3.14	1.54 ± 0.92	0.22
Body mass index (g/m^2)							
< 25	131	16.4 ± 8.4	18.0 ± 8.6	0.29	1.63 ± 2.20	1.58 ± 1.27	0.88
≥ 25	69	16.5 ± 8.7	21.6 ± 9.4	0.02	2.29 ± 4.07	1.50 ± 0.95	0.30
Hypertension (%)							
No	149	15.6 ± 7.5	18.4 ± 8.8	0.04	1.74 ± 2.72	1.57 ± 1.19	0.61
Yes	51	18.8 ± 10.3	23.1 ± 9.2	0.13	2.02 ± 3.23	1.48 ± 1.01	0.41
High-sensitivity C-reactive protein (mg/dL)							
< 50th	100	14.7 ± 6.9	19.1 ± 9.0	0.01	1.33 ± 1.05	1.48 ± 0.88	0.44
≥ 50th	100	18.5 ± 9.6	19.8 ± 9.2	0.48	2.40 ± 4.01	1.60 ± 1.32	0.19
Fasting glucose (mg/dL)							
< 100	167	16.8 ± 8.7	19.1 ± 9.4	0.11	1.87 ± 3.0	1.49 ± 1.14	0.26
≥ 100	33	13.4 ± 5.5	20.9 ± 7.9	0.01	1.38 ± 0.97	1.74 ± 1.14	0.37
Smoking habit							
Yes	146	17.2 ± 10.3	19.7 ± 9.0	0.33	2.57 ± 4.67	1.39 ± 0.77	0.24
No	54	16.2 ± 7.9	19.4 ± 9.2	0.03	1.61 ± 1.16	1.63 ± 1.29	0.95
Alcohol habit							
Yes	53	17.2 ± 8.7	21.2 ± 8.4	0.10	1.67 ± 1.07	1.48 ± 0.93	0.52
No	147	16.3 ± 8.4	18.5 ± 9.4	0.13	1.85 ± 3.11	1.58 ± 1.25	0.48
Coffee							
Yes	126	16.0 ± 8.4	18.3 ± 8.4	0.13	1.88 ± 3.32	1.62 ± 1.17	0.52
No	74	17.4 ± 8.4	20.9 ± 9.8	0.12	16.5 ± 10.7	14.7 ± 11.2	0.48
Tea							
Yes	148	16.4 ± 8.0	19.7 ± 8.6	0.02	1.98 ± 3.49	1.51 ± 1.0	0.28
No	52	16.5 ± 9.1	18.1 ± 12.4	0.64	15.3 ± 11.5	18.2 ± 19.0	0.63

[a] Regression model estimates adjusting for age and gender, and data are expressed as mean ± standard deviation in subgroup analyses.

Oregon, USA). Forest environment monitoring data were collected by the environmental monitoring system from January 6 to 10, 2014. The SO_2, NO_x, CO, O_3, temperature, and relative humidity measurements were recorded daily every minute throughout the examination period.

The air conditioning in this building is a central control system. To obtain the indoor monitoring data of the urban environment, the same environmental monitoring system was set up in the commercial building to record daily data every minute from January 14 to 17, 2014. For each hour, air quality data were extracted from a monitoring data system and averaged to one result for each air pollutant. In addition, daily measurements of outdoor monitoring data of the urban environment from the Taipei air quality monitoring stations operated by the Taiwan Environmental Protection Administration were applied during the study period from January 14 to 17, 2014. The monitoring stations were fully automated and provided hourly readings of SO_2 (Ecotech 9850B, Australia) and NO_x (Ecotech 9841B, Australia) by ultraviolet fluorescence, CO (Horiba APMA360, Japan) by non-dispersive infrared photometry, O_3 (Ecotech 9810B, Australia) by ultraviolet photometry, temperature, and relative humidity (083C, Met One Inc., Oregon, USA).

For each participant, blood pressure was measured twice after at least 5 min of rest in a sitting position. The

Table 6: Effects of exposure to a forest environment on NK cell and activating NK cell

(A) Comparisons before and after the forest trip in Xitou for five days				
***N* = 11**	**Pre-forest trip**	**Post-forest trip**	**Paired-difference**	***p*-value[a]**
NK cell level (%)	22.49 ± 11.76	23.72 ± 15.05	1.23	0.411
Activating NK cell (%)	0.83 ± 0.39	1.72 ± 0.1	0.89	0.002
(B) Comparisons before and after the forest trip and four days after returning to Taipei				
***N* = 7**	**Pre-forest trip**	**Four days after**	**Paired-difference**	***p*-value**
NK cell level (%)	20.51 ± 11.27	20.98 ± 10.99	0.47	0.746
Activating NK cell (%)	0.77 ± 0.38	1.13 ± 0.43	0.36	0.004

[a]*P*-value by using paired *t*-tests.

Participant characteristics: data was shown in average.

(A) group: age, 60.4 years; body mass index, 23.54 kg/m^2; male, 27.3%; high-sensitivity C-reactive protein, 0.12 mg/L; systolic blood pressure, 113 mmHg.

(B) group: age, 61.8 years; body mass index, 23.57 kg/m^2; male, 14.3%; high-sensitivity C-reactive protein, 0.13 mg/L; systolic blood pressure, 106 mmHg.

blood samples were obtained after overnight fasting for 10–14 hours via the antecubital vein for each participant. Low- and high-density lipoprotein cholesterol (LDL-C and HDL-C), plasma glucose and serum levels of cholesterol, and triglycerides were measured using an auto-analyzer (Toshiba, TBA-200FR; Toshiba, Tokyo, Japan). Serum high-sensitivity C-reactive protein (hs-CRP) was measured using chemiluminescent enzyme-labeled immunometric assay (Immulite C-Reactive Protein, Diagnostic Products Co., Los Angeles, USA).

Blood sample preparation and flow cytometry analysis

The samples were prepared according to the method described by Jackson et al. 1986 [31]. Freshly isolated peripheral blood lymphocytes (PBLs) were stained with immunomodulatory agents by following combinations of directly labeled monoclonal antibodies (mAbs): CD3 piperidinin-chlorophyll conjugate (PerCP)/CD56 PE/CD69 fluorescein isothyocyanate (FITC) (Becton Dickinson, CA, USA) for 30 minutes at 4°C in the dark. After incubation cells were suspended with 8 mL of a 1/10 dilution FACS Lysing solution (BD Biosciences) in the dark for 20 min at room temperature. Cells were centrifuged at 1500 rpm for 5 minutes for removing the supernatant. Cells were then washed with PBS twice by centrifugation at 1500 rpm for 5 minutes. Finally, the supernatant was discarded and the cells suspended in 200 μL of PBS for flow cytometry analysis. NK cell level was defined as $CD3^-/CD56^+$ population. Activating NK cell was defined as $CD3^-/CD56^+/CD69^+$ population. Surface marker expression was quantified on a FACSVerse flow cytometer (Becton Dickinson). A total of 20,000 gated events verified as lymphocytes according to their physical characteristics (forward scatter and side scatter) were collected per sample. The results were expressed as the percent of a cell subset using CellQUEST software.

Statistical analyses

We compared the general characteristics and percentage of NK cells and activating NK cells in the forest and urban groups. The *t*-test was used to detect differences in the group means for the characteristic variables if they were continuous and normally distributed, whereas the chi-squared test was applied to categorical data. Continuous variables were expressed as the mean ± standard deviation, and binary variables were expressed as percentages.

The environmental conditions were compared based on the air quality and meteorological data collected in the forest and urban environments. The complete blood cell counts were also compared between the forest and urban groups. The percentages of NK cells and activating NK cells in the forest and urban groups were compared using the crude value and regression model adjusted value after adjusting for age and gender.

The percentages of NK cells and activating NK cells in the forest and urban groups were also compared through subgroup analyses, including age, gender, BMI, hypertension, hs-CRP, and fasting glucose. The percentages of NK cells and activating NK cells before and after a short-term forest trip were compared through a paired *t*-test to detect intra-individual differences among participants. All the statistical analyses were performed with SAS statistical software (version 9.2, SAS Institute Inc., Cary, NC, USA).

CONFLICTS OF INTEREST

The authors declare that no conflicts of interest.

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Restorative Qualities of and Preference for Natural and Urban Soundscapes

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Psychological restoration in urban agglomerations has become a growing challenge. Although scientific proof of the significance of nature is irrefutable, an increase in built-up areas has led to a decrease in urban greenery. Thus, a growing need for restorativeness in urban surroundings has emerged. To investigate whether positively evaluated sonic environments, represented by natural and urban sounds, have comparable restorative qualities we conducted two studies. The aim of the first (Study 1) was to explore the restorative qualities of positively assessed natural and urban sounds. Participants (N = 88) were asked to listen and to rate 22 recordings (each 1 min long) either from natural or urban environments. In the second (Study 2) we investigated whether positively evaluated sonic environments (natural and urban), demand for restoration (feeling relaxed or fatigued) and company (being alone or with a friend) affect the restorative qualities of natural and urban soundscapes. After reading assigned scenarios (feeling relaxed or fatigued; being alone or with a friend), participants (N = 120) were asked to imagine a walk in presented sonic environments and to complete forms (one for each sonic environment) concerning the restorative qualities of given soundscapes (natural and urban). Top five recordings of natural and urban sonic environments were selected from Study 1 and combined into a 154-s soundtrack, to provide a background for the imagined walks in both settings. Our findings confirmed that natural sounds are perceived more favorably than urban recordings. Even when only the most positively assessed soundscapes were compared, nature was still perceived as being more restorative than urban areas. Company of a friend was found to be more beneficial in the urban surroundings, particularly when there was no need for restoration.

Keywords: restoration, restorative qualities, sounds, sonic environment, natural soundscapes, urban soundscapes, preference

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INTRODUCTION

A recent report of the United Nations (2015) predicts that sixty-six percent of the world population will reside in urban areas by the year 2050. As progressive urbanization seems inevitable, it is essential to seek restorativeness in urban surroundings. Surprisingly, despite researchers' growing interests in the affordances of various environments, relatively little is known about the restorative qualities of urban areas. Even less explored is the potential of positively assessed urban sounds, which are omnipresent and accompany citizens in their everyday routines.

Research has shown that people's encounters with natural environments translate into numerous psychological benefits such as improved cognitive functions (Tennessen and Cimprich, 1995; Hartig et al., 2003; Berto, 2005; Berman et al., 2008, 2012; Faber Taylor and Kuo, 2009; Kaplan and Berman, 2010), lessened anger (Cackowski and Nasar, 2003; Kweon et al., 2008), boosted positive affective states (Berman et al., 2008, 2012; van den Berg and Custers, 2011) and reduced stress (Ulrich et al., 1991; Parsons et al., 1998; Wells and Evans, 2003; Kweon et al., 2008; van den Berg et al., 2010; van den Berg and Custers, 2011; Ward Thompson et al., 2012; Hartig et al., 2014).

Urban environments' positive contributions, meanwhile, have remained obscure, attracting less scholarly attention. Nevertheless, findings from settings such as museums (Kaplan et al., 1993; Packer, 2008), monasteries (Ouellette et al., 2005), or houses of worship (Herzog et al., 2010) have highlighted the positive aspects of man-made surroundings and confirmed that urban environments may also afford mental recovery. In addition, participation in cultural life (e.g., going to the cinema, theater, or concerts) was found to be positively related to perceived health and well-being (Johansson et al., 2001), and attending sporting events and cultural activities was associated with high life satisfaction and good health (Leadbetter and O'Connor, 2013). Due to the fact that well-being and life satisfaction appear to be related to mental recovery (Sonnentag and Fritz, 2015), there is a distinct possibility that urban facilities, in particular those associated with sport and culture, can also contribute to restoration.

Two complementary approaches explain mechanisms behind the restorative effects of environments, the Attention Restoration Theory (ART; Kaplan and Kaplan, 1989; Kaplan, 1995), and the Stress Recovery Theory (SRT; Ulrich, 1983; Ulrich et al., 1991). Although both refer mostly to nature, it has been confirmed that they apply also to the urban surrounding (Kaplan et al., 1993; Ouellette et al., 2005; Herzog et al., 2010).

In line with the former approach (ART) to achieve a restorative effect, an environment should have the ability to reconcile individual desires and goals with environmental demands ('compatibility'), be perceived as coherent and of substantial scope ('extent'), create a sense of psychological distance from the problems of everyday life ('being away'), and induce 'fascination' (Kaplan and Kaplan, 1989; Kaplan, 1995). In some built environments additional factors play a role. For example, 'spirituality' is characteristic for places that serve religious purposes, such as monasteries (Ouellette et al., 2005) or houses or worship (Herzog et al., 2010), while 'comfort,' related to the original property of 'compatibility' (Kaplan et al., 1993), defines places such as museums. Other features, meanwhile, may be imperceptible, as was the case with 'compatibility' in a study by Herzog et al. (2010). Interestingly, these properties can also be linked. 'Beauty,' for example, can be described as a combination of 'fascination,' 'extent,' and 'aesthetics' (Ouellette et al., 2005; Herzog et al., 2010).

The Attention Restoration Theory (Kaplan and Kaplan, 1989; Kaplan, 1995) holds that recovery from mental fatigue occurs through the restoration of depleted cognitive resources. Kaplan (1995) distinguishes two types of attention: stimuli-driven involuntary attention, which does not require mental effort, and directed attention, which is responsible for intentional actions and everyday behaviors. Involuntary attention, due to its bottom-up mechanism (Berman et al., 2008), provides psychological restoration, as attention is automatically captured by fascinating stimuli (Beute, 2014), whereas directed attention requires more conscious control, and when depleted, leads to deterioration of cognitive functions and, subsequently, to a reduction in the ability to adapt to daily demands (Kaplan and Kaplan, 2003).

In line with Stress Recovery Theory (Ulrich, 1983; Ulrich et al., 1991), apart from coping with mental fatigue, restoration can also be explained in terms of the physiological reaction to stress (Ulrich, 1983; Ulrich et al., 1991). Particularly relevant seems the importance of positive affective reactions, which according to Ulrich et al. (1991, p. 224), are "comprised of likening and moderate to high interest, should motivate and sustain prolonged attention/intake, should produce higher levels of positive feelings, reduce negatively toned or stress related feelings such as fear and anger, and suppress stressful or extraneous thoughts (Ulrich, 1981, 1983)."

A vast amount of literature attests to people's preferences for natural settings. Nonetheless, these findings might be to some extent affected by the selection of urban stimuli. Despite Ulrich's emphasis on positive affective reaction (Ulrich et al., 1991), in previous works, urban surroundings have often been represented either by unattractive images of industrial zones (Purcell et al., 2001), streets and buildings (Purcell et al., 2001; Joye et al., 2013), which are usually accompanied by automobile traffic (Emfield and Neider, 2014), or by unpleasant audio stimuli such as office noise (Jahncke et al., 2015), sounds of busy intersections, construction site clamor (Medvedev et al., 2015), traffic noise (Gidlöf-Gunnarsson and Öhrström, 2007; Alvarsson et al., 2010), or Time's Square's cacophony of conversations, cars, and honks (Emfield and Neider, 2014).

Moreover, conclusions on people's preference for natural or urban environments have mostly relied on visual stimuli (Herzog et al., 1997; Purcell et al., 2001; Staats et al., 2003; Staats and Hartig, 2004; Nordh et al., 2009; Joye et al., 2013; Stevens, 2014; Conniff and Craig, 2016). Scarce evidence shows, however, that sonic stimuli, such as positively assessed bird songs or sounds of water may also contribute to psychological restoration (Ratcliffe et al., 2013).

As argued by Ulrich (1983), as well as Conniff and Craig (2016), concentrating exclusively on a visual sensory channel limits our understanding of often complex environments, because photography can depict a given setting only fragmentarily (Nordh et al., 2009). Sound, by contrast, can contribute to a more holistic interpretation of a given surrounding, because of its own restorative potential (Alvarsson et al., 2010; Abbott et al., 2016). The impact of the audio stimuli on the assessment of the environment is reflected in the studies investigating a reciprocal relationship between sound and vision. It has been revealed that natural sounds can positively influence perception of images portraying natural or man-made settings (Carles et al., 1999; Hedblom et al., 2014), whereas deterioration in the sonic environment reduces the evaluation of the surroundings (Carles et al., 1999). Likewise,

vision can modify the perception of the audio stimuli (Viollon and Lavandier, 1997; as cited in Carles et al., 1999).

Whereas visual and multimodal approaches have been discussed quite frequently, the relationship between positive evaluation of urban sounds and their restorative qualities have been given much less attention. Therefore, the purpose of this paper is to explore the restorative potential of urban soundscapes. In a pair of studies, we want to verify whether restorative qualities of natural and urban sounds are comparable. In Study 1 we aim to explore people's preference for recorded natural vs. urban sounds and their restorative qualities. The objective of Study 2 is to investigate whether the demand for restoration and company of others play a role in the perception of urban sounds' restorative qualities.

STUDY 1

In line with the abundant existing literature on visual stimuli, we expected that, in general, natural sounds would be evaluated more positively than urban sounds (Hypothesis 1). We also hypothesized that natural sonic environments will be rated as more restorative than urban sonic environments (Hypothesis 2). Additionally, due to the nature of the urban sonic environment, which is usually louder and noisier than nature, we predicted that sensitivity to sounds would play a role in the assessment of the recordings. We expected that the higher the sensitivity to sounds, the less positive the evaluation of the urban sounds would be (Hypothesis 3). We also aimed to select the most positively assessed sounds of both sonic environments.

Method

Participants

Eighty-eight students from the SWPS University of Social Sciences and Humanities (78% women), aged 19–44 years ($M = 26.74$, $SD = 6.82$), were recruited for the study through an advertisement placed in the university's building and on its website. All gave informed consent after the short introduction to the study. They were rewarded with credit points and had a chance to win a lottery gift worth, on average, 5$. The study was approved by the ethics committee of the authors' faculty.

Materials and Measures

Sounds

High-quality (16 bit, 44.1 kHz) samples representing 22 natural environments and 22 urban environments (**Table 1**) were binaurally recorded by a sound recordist. The presence of people was minimized wherever possible while taking these samples so that the focus could be on the environmental sounds. However, there were some exceptions, such as a café, swimming pool, ice rink and parade, where people's voices could be heard in the background. The audio levels were normalized; each 1-min recording was scaled following Medvedev et al.'s (2015) example to an average sound level of 64 dB SPL, and saved as a WAV file.

Evaluation of the sounds

To assess how positive and/or negative each recording was perceived to be, participants used the Evaluative Space Grid (Larsen et al., 2009). The responses were given on a 5 × 5 grid (25 cells) presented on the paper form. On the *x*-axis, ranging from 'Not at all' (0) to 'Extremely' (4), participants were asked how positive they felt about the stimulus, whereas on the *y*-axis, also ranging from 'Not at all' (0) to 'Extremely' (4), they were asked how negative they felt about the stimulus. The answers were then averaged. The negative evaluation was not analyzed in this study.

Sensitivity to sounds

Participants' sensitivity to sounds was measured using the Hyperacusis Questionnaire (Khalfa et al., 2002). On this measure, consisting of 14 questions (e.g., 'Are you particularly sensitive to or bothered by street noise?'), the responses were given on a 5-point scale, ranging form 'No' (0) to 'Yes, a lot' (4) and then averaged. Three additional questions concerning the experience of being exposed to noise ('Are you or have you been exposed to noise?', tolerance to noise ('Do you tolerate noise less well as compared to a few years ago?') and eventual hearing problems ('Have you ever had hearing problems? If so, of what kind?') were responded to by choosing 'Yes' (1) or 'No' (0).

According to Khalfa et al. (2002), the mean total score for the questionnaire is 15 ± 6.7, and a result above 28 (out of the maximum score of 42) may be an indicator of auditory hypersensitivity. In our research the Cronbach's alpha for the scale was 0.76.

Restorative qualities of sounds

Each sound's restorative quality was assessed with four items inspired by the properties of the Attention Restoration Theory (Kaplan and Kaplan, 1989; Kaplan, 1995): being away ('How often this sonic environment can facilitate a sense of mental detachment from the problems of everyday life?'), fascination ('How often this sonic environment can induce fascination/interest?'), compatibility ('How often this sonic environment can encourage you to find yourself in this environment?') and extent ('How often this sonic environment can offer many opportunities to act in such area?'). The answers were given on a 5-point scale ranging from: 'Never' (1) to 'Very often' (5) for questions concerning properties of being away and compatibility, and from 'Very often' (1) to

TABLE 1 | Sounds used in Study 1.

Natural environment
Blackbird in a clearing, Blackcap in the woods, Corncrake at a pond, Crows, Deer in the rut, Forest (boar and birds), Frogs at a pond, Great reed warbler, Howling wolves, Larks and barred warbler, Meadow in the spring (many birds species), Night in the woods (eagle-owls and wind), Nightingale, Ravens, River, Robin at a river, Sea, Seagulls on a windy day, Summer night (crickets and birds), Swarm of insects, Thunderstorm, Wren at a stream
Urban environment
Airport (airplane landing), Street (ambulance), Old town (barrel organ), Café, Amusement park (carousel), Church bells, Concert (orchestra tuning and applause), Construction site, Fireworks display, Highway, Ice rink (people skating), Lawn mower, Parade (brass orchestra), Road work (pneumatic hammer), Fire department (siren), Street noise, Subway (empty subway car), Swimming Pool, Traffic jam (with car horns), Train, Video arcade, Wind chimes

'Never' (5) for questions concerning properties of fascination and extent. To ease the calculations, the responses were later recoded (from 0 for 'Never' to 4 for 'Very often') and averaged. Cronbach's alpha for the scale was 0.93 (for all natural sounds' restorative qualities) and 0.84 (for all urban sounds restorative qualities). For the top five sounds of both environments, Cronbach's alpha was also calculated and was 0.89 (for natural recordings) and 0.81 (for urban recordings). Additionally, we asked participants whether they recognized the presented recording ('Yes' or 'No') and, if the answer was affirmative, to identify the given sound (an open question).

Procedure

Each participant took part in the study individually. After a brief instruction on the procedure, participants were randomly assigned to the natural or urban condition. Subsequently, they listened to and evaluated 22 recordings from natural or urban environments (depending on the condition), played via closed-back headphones (they had the opportunity to adjust the sound volume according to their needs). After each recording, participants rated how positive and negative they felt about the stimulus using the Evaluated Space Grid (Larsen et al., 2009). Then, they were asked whether they recognized the sound and evaluated each sound's restorative quality. A 22 × 22 Latin square in a Williams design (Latin Squares – Williams Design, n.d.) was used to eliminate order effect. The time needed to complete each questionnaire before the next recording was played was adjusted to each participant's individual needs. After all recordings were played, participants completed the Hyperacusis Questionnaire (HQ) and basic socio-demographic data. The study lasted around 40 min on average.

Results

Evaluation of All Sonic Environments

We found a significant difference in the evaluation of all recordings, Welch's $F(1,55.12) = 23.88$, $p < 0.001$, est. $\omega^2 = 0.21$. As predicted (Hypothesis 1), the natural sounds were perceived more positively ($M = 2.12$, $SD = 0.65$) than the recordings from the urban environments ($M = 1.55$, $SD = 0.33$). In line with expectations (Hypothesis 2), they were also rated as being more restorative ($M = 8.63$, $SD = 1.44$) than urban recordings ($M = 6.67$, $SD = 1.01$), $F(1,81) = 52.39$, $p < 0.001$, $\eta^2 = 0.39$. Further analysis revealed that evaluation of the sounds was positively correlated with their perceived restorative qualities, both for the natural, $r = 0.78$, $p < 0.001$, and urban, $r = 0.52$, $p < 0.001$, sonic environments.

Participants had no major problems identifying the sounds. The most recognizable sounds of the natural environment turned out to be: a blackcap in the woods (100% recognition), crows (100%), howling wolves (100%), insects (100%), the sea (100%), seagulls on a windy day (100%), a thunderstorm (100%), a wren at a stream (100%); the least recognizable were the recordings of a boar (64%) and a deer in the rut (66%). It should be noted that the knowledge of bird species was not required. As for the urban environment, the most recognizable sounds were: an airplane landing (100%), an ambulance (100%), a café (100%), church bells (100%), a fireworks display (100%), a parade (100%), and a traffic jam (100%), whereas the least recognizable were: an ice rink (71%) and a subway (57%). Interestingly, not all who declared sound recognition identified the recordings appropriately (e.g., the deer was taken for marine mammals).

The mean total score for the Hyperacusis Questionnaire (Khalfa et al., 2002) was 15.78 ($SD = 6.41$). Only 3.41% of participants met the criteria of hypersensitivity to sounds (results above 28). Still, positive correlation between participants' sensitivity to sounds and the positive evaluation of the natural sounds was found, $r = 0.42$, $p < 0.01$. Surprisingly, an increase in sensitivity to sounds turned out to be correlated with a more positive assessment of the natural sounds. Contrary to our expectations (Hypothesis 3), the correlation between sonic urban environments and sensitivity to sounds was non-significant, $r = -0.20$, $p = 0.19$.

Most Positively Evaluated Sonic Environments (Natural and Urban)

On the basis of the means of all sounds used in this study (Supplementary Table 1), the five most positively assessed recordings (**Table 2**) from each environment were selected. The chosen recordings in natural settings were: a robin at a river, a wren at a stream, a blackbird in a clearing, the sea, and a blackcap in the woods. The chosen recordings in urban settings were: a concert (an orchestra tuning and applause), a fireworks display, an old town sound (a barrel organ), an amusement park (a carousel), and a café.

A significant difference was found between the evaluations of the sonic environments, $U = 640.00$, $p < 0.01$. Again, natural sounds were perceived more positively ($Mdn = 3.40$) than urban recordings ($Mdn = 3.00$). Furthermore, natural sonic environments were rated as being more restorative ($M = 12.12$, $SD = 1.90$) than urban recordings ($M = 11.17$, $SD = 1.82$), $F(1,86) = 5.71$, $p < 0.05$, $\eta^2 = 0.06$. As was previously discovered, the evaluation of the sounds was found to be correlated with perceived restorative qualities of the top five natural sounds, $r_s = 0.80$, $p < 0.001$, and for the top five urban recordings, $r_s = 0.61$, $p < 0.001$.

The relationship between a participant's sensitivity to sounds and the evaluations of the sonic environments was also examined. Neither the correlation between auditory sensitivity and natural sound assessments ($r_s = 0.28$, $p = 0.06$) nor the correlation between auditory sensitivity and urban sound assessments ($r_s = -0.19$, $p = 0.23$) was significant, possibly suggesting that sensitivity to sounds did not influence the evaluations of positive sonic environments.

TABLE 2 | The most positively assessed sounds of natural and urban environments in Study 1 (mean values, standard deviations).

Natural environment	*M*	*SD*	Urban environment	*M*	*SD*
Robin at a river	3.48	0.82	Concert	3.59	0.62
Wren at a stream	3.43	0.93	Fireworks display	2.95	1.06
Blackbird in a clearing	3.14	1.00	Old town	2.80	0.95
Sea	3.09	0.88	Amusement park	2.77	0.99
Blackcap in the woods	3.02	1.05	Café	2.77	1.16

Discussion

As expected, our study confirmed that natural environments, represented by sound stimuli, are perceived more favorably than urban surroundings. This is quite intuitive, as it could have been predicted that negatively perceived natural sounds, such as a crow's call (Ratcliffe et al., 2013), are still less disturbing than some intrusive urban sounds (e.g., recording of a pneumatic hammer). We found, however, that even positive assessment of the urban sounds cannot equalize the difference in how both environments are perceived.

The high percentage of sound identification shows that both sonic environments were familiar to participants, so there may be a different explanation of these results, other than distinct familiarity with the soundscapes. It is possible, for example, that people find urban surroundings more heterogeneous than nature and that participants' individual preferences toward the given settings (even when sonic) are reflected in the study. Our findings seem to confirm that. Whereas natural sounds were almost unanimously assessed positively (in particular birdsongs and water-related soundscapes), the ratings of urban recordings varied. It is likely that some participants found the sonic atmosphere of the urban area as a model example of the environments conducive to recreation and social life, while others described the same setting as undesirable: fatiguing, too noisy, or even aesthetically unappealing.

In line with our assumptions, natural recordings were also perceived as being more restorative than urban soundscapes, both for all and for the top five sounds from natural and urban environments. It was also confirmed that evaluations of the sounds were positively correlated with their perceived restorative qualities, especially in the natural sonic environment.

Surprisingly, sensitivity to sounds did not affect the perception of urban sounds, neither for all recordings nor for the top five. It did, however, influence the assessment of all natural sounds. These results may indicate that, despite preferring natural recordings, people who are sensitive to sounds has become highly accustomed to urban soundscapes. The most positively assessed sounds, meanwhile, are not intrusive, so their origin does not matter.

To further explore the relationship between positive evaluation and restorativeness, we decided to conduct another study, in which we wanted to more thoroughly examine soundscapes' restorative qualities. Due to the fact that sensitivity to sounds did not turn out to significantly influence the perception of urban soundscapes and considering that we had already selected the most positively assessed sounds of both sonic environments (taking sensitivity to sounds into account), we decided to exclude sensitivity to sounds from further research. Instead we decided to concentrate on additional factors that can influence soundscapes' restorative qualities – company and the demand for restoration.

STUDY 2

In Study 2, we further investigated whether positively evaluated urban surroundings can afford psychological restoration comparable to natural settings. For this purpose we replicated the study by Staats and Hartig (2004), in which participants were asked to imagine themselves in a given environment during an imagined walk with a friend or alone. Instead of visual presentation of environments, we used positively assessed sound stimuli.

We were interested in whether a presence in a given setting, even when imagined, can affect its perceived restorative quality. As a sonic background for the imagined walk we chose the most positively evaluated recordings from Study 1. Based on the results from Study 1, we expected that there would be a significant difference between natural and urban soundscapes' restorative qualities (Hypothesis 1).

Additionally, inspired by Staats and Hartig (2004), we decided to verify how company and the demand for restoration (feeling attentionally fatigued or relaxed) interplay with positively assessed soundscapes from natural and urban environments. We expected that participants would experience more restoration being in company, both in the natural (Hypothesis 2a) and in the urban (Hypothesis 2b) soundscapes. We also predicted that demand for restoration would affect the evaluation of restorative qualities: it was expected that participants from the attentionally fatigued condition would rate an imagined walk in the natural soundscapes as being more restorative than an imagined walk in the urban sonic environment (Hypothesis 3a), whereas participants from the relaxed condition, due to the use of stimuli representing positively assessed soundscapes, would rate an imagined walk in the urban soundscapes as being more restorative than an imagined walk in the natural sonic environment (Hypothesis 3b). It was also predicted that there would be a difference in the evaluation of the imagined walk in the natural and the urban soundscapes (Hypothesis 4).

In addition, we wanted to determine whether and how a sense of security influences the restorative qualities of positively perceived sonic environments. We assumed that the urban soundscapes would invoke a greater sense of security than the natural soundscapes (Hypothesis 5). It was also expected that those who imagine themselves walking with a friend would feel more secure than those who imagine themselves walking in solitude, both in the natural (Hypothesis 6a) and the urban (Hypothesis 6b) soundscapes. Moreover, we predicted that a sense of security would have an indirect effect on restorative qualities both in the natural (Hypothesis 7a) and the urban (Hypothesis 7b) sonic environments through company. Likewise, we expected that a positive evaluation of an imagined walk would have an indirect effect on restorative qualities in the natural (Hypothesis 8a) and the urban (Hypothesis 8b) soundscapes through company.

Method

Participants

One hundred and twenty participants (78% women) aged 18 to 51 years ($M = 25.41$, $SD = 8.38$) took part in the study. All were students of the SWPS University of Social Sciences and Humanities who responded positively to the announcement about this research that was placed in the university's building and

on its website. Each participant signed the informed consent form that outlined the procedure's steps, and was rewarded with credit points and a chance to win a lottery gift worth, on average, 5$. The study was approved by the ethics committee of the authors' faculty.

Materials and Measures

Sound recordings

The most-positively assessed sounds from Study 1 (**Table 2**) were used: five natural (a robin at a river, a wren at a stream, a blackbird in a clearing, the sea, and a blackcap in the woods), and five urban recordings (a concert, a fireworks display, a barrel organ, a carousel, and a café). However, this time, to facilitate the listening procedure, each sound was shortened to 30 s, as advised by participants of Study 1, and then combined with others (with 1-s transitions) into a single 154-s soundtrack to provide a background for the imagined walks in the natural and urban settings. Each sound in the compilation represented one place on the 1-h walking route, which, depending on the participant's imagination, could have been either visited or just passed by.

Scenarios

Questionnaires and scenarios used in this study were based on translations of the items and scenarios described by Staats and Hartig (2004).

Demand for restoration scenario. Two alternative scenarios of demand for restoration were created. In a random manner, participants were asked either to imagine themselves being attentionally fatigued (one half of participants) or completely relaxed (the other half). In the former, participants were instructed to visualize a state of tiredness at the end of a semester, when problems with concentration and negative emotions occur. In the latter, participants were instructed to imagine a state of relaxation after the summer holidays, when feelings of restoration, energy, and preparedness to concentrate on learning occur. The demand for restoration scenario remained unchanged throughout the course of the study.

Company scenario. Two versions of a story were prepared. In both, participants were asked to imagine themselves strolling for an hour in the environment, which was represented by the sounds they were about to hear (natural or urban). In one version, the participants were instructed to imagine a lonely walk, without anyone they knew. In the other, they were to imagine walking with someone close to them, for example, with a friend. Again, participants were randomly assigned to one of these two scenarios, and the scenario remained unchanged throughout the study.

Manipulation checks

Manipulation checks consisted of eight items measuring affective state (feeling irritated, tired, exhausted, mentally drained) and attention depletion (ability to make a decision, concentrate, predict consequences of a complex situation, focus attention during a long lecture). Participants indicated to what extent they agreed or disagreed with each sentence using a scale from 'Completely not' (1) to 'Very much' (7). The scale for attention depletion was reversed, and the mean across all eight items was calculated. The Cronbach's alpha for manipulation checks was 0.93.

Restorative qualities of the imagined soundwalks

Participants rated the restorative qualities of an hour-long walk in sonic environments (natural and urban), assuming they were either attentionally fatigued or relaxed. They were asked 19 questions, based on the work of Staats et al. (2003), about the benefits of an hour-long walk in the given soundscapes. The items concentrated on psychological restoration (e.g., 'Experience of restoration' or 'Regain an ability to concentrate'), reflection (e.g., 'Thinking about important matters' or 'View things from a new perspective'), and social stimulation (e.g., 'Seeing many different people' or 'Noticing many different things surrounding you'). The answers were measured on a Likert-type scale ranging from 'Most unlikely' (1) to 'Extremely likely' (7) and then averaged. Cronbach's alpha was similar: 0.87 for natural soundscapes, and 0.88 for urban soundscapes.

Additionally, a similar set of items was used to assess the pleasantness of an imagined walk, with answers ranging from 'Very unpleasant' (1) to 'Very pleasant' (7), however, the results were not analyzed in this study.

Sense of security

Participants' sense of security in natural and urban soundscapes was measured. They rated how secure they felt in the given sonic environment on a 7-point scale from 'Completely not' (1) to 'To a very high degree' (7).

Evaluation of the imagined soundwalks

The imagined soundwalks were evaluated using additional rating instruments. Participants were asked to indicate how attractive, nice, positive, and enjoyable an hour-long walk in a given sonic environment would be. Each of the four answers was given on a Likert-type scale ranging from 'Completely not' (1) to 'To a very high degree'(7). The means were calculated separately for both soundscapes. Cronbach's alpha was, respectively, 0.87 for the evaluation of the walk in natural soundscapes, and 0.89 for the evaluation of the walk in urban soundscapes.

Control measures

For each sonic environment, two additional questions were asked: one about the familiarity of the soundscapes and one about the representativeness of its positively assessed sounds. Answers were given on a Likert-type scale ranging from 'Not at all' (1) to 'Very' (5). Additionally, the question about familiarity of the state of attentional fatigue or relaxation (depending on condition) was added. This answer was also given on a 5-point scale ranging from 'Not at all' (1) to 'Very' (5). An open question for comments and opinions about the research was included. Demographic data such as age and gender were also collected.

Procedure

We followed the procedure used by Staats and Hartig (2004), with the exception that the photographic slides illustrating classic natural and urban settings (e.g., forest scenes, shopping streets) were replaced with audio stimuli, representing only positively assessed sonic environments from Study 1.

Participants, randomly assigned to conditions ($n = 30$ per group), were seated in the middle of a room in front of a pair of sound speakers; individually or in small groups (up to 6 people). After detailed instruction, they read about the demand for a restoration scenario of feeling relaxed or attentionally fatigued and completed the first questionnaire composed of manipulation checks and items measuring pleasantness of an imagined hour-long walk. Next, they read another short text – a company scenario of being alone or with a friend and the first group of environmental sounds (natural or urban) were played, the order of which was balanced: one half of participants heard the set of urban recordings, while the other half heard the set of natural sounds. Each set of soundscapes was presented twice: the first time when the participants were to imagine themselves passing five different locations during an imagined hour-long walk according to prior scenarios, and the second time to refresh their memories and to accompany the questionnaires about the evaluation of the imagined walks and their restorative qualities. The whole procedure was repeated with the other set of sounds, and another questionnaire with identical questions was used. The overall session time averaged 30 min. The scheme of the procedure used in the study is presented in **Figure 1**.

Results

In this section we first present the results of manipulation checks and preliminary analyses. Then we report the effects of the restorative qualities of the imagined soundwalks. Later in the text we discuss the evaluation of the imagined soundwalks and the influence of sense of security on the obtained results.

Manipulation Checks and Preliminary Analyses

We verified whether participants indeed met the given condition of demand for restoration after reading the assigned scenarios. As assumed, those instructed to imagine themselves in a state of attentional fatigue indicated being more fatigued ($M = 4.87$, $SD = 0.80$) than those instructed to imagine themselves relaxed ($M = 2.16$, $SD = 0.69$), $t(118) = -19.91$, $p < 0.001$. The difference in familiarity between the conditions was not significant, $t(118) = -1.30$, $p = 0.20$: participants were familiar with their assigned states of being attentionally fatigued ($M = 4.50$, $SD = 0.73$) or relaxed ($M = 4.33$, $SD = 0.68$).

The natural sonic environment was perceived as more familiar to participants ($M = 4.63$, $SD = 0.71$) than the urban sonic environment ($M = 4.28$, $SD = 0.90$), $t(119) = 3.39$, $p < 0.01$, and recordings of the positively assessed natural soundscapes were perceived as more representative ($M = 4.74$, $SD = 0.51$) than those representing positively evaluated urban soundscapes ($M = 3.76$, $SD = 0.96$), $t(119) = -10.55$, $p < 0.001$.

Effects of the Restorative Qualities of the Imagined Soundwalks

A 2 × 2 × 2 mixed ANOVA was carried out to analyze the effects of the restorative qualities of the imagined soundwalks with the type of soundscapes (natural vs. urban) as a within-subjects variable and company (alone vs. with a friend) and demand for restoration (feeling attentionally fatigued vs. relaxed) as between-subjects variables.

As assumed (Hypothesis 1), the results yielded a significant main effect of soundscapes' restorative qualities, $F(1,116) = 84.37$, $p < 0.001$, $\eta_p^2 = 0.42$ revealing that participants preferred an imagined walk in the natural soundscapes ($M = 5.38$, $SD = 0.68$) over an imagined walk in the urban soundscapes ($M = 4.61$, $SD = 0.82$).

The main effect of company was statistically significant, $F(1,116) = 5.56$, $p < 0.05$, $\eta_p^2 = 0.05$. Participants rated sonic environments as being more restorative when they imagined themselves in the company of a friend. However, simple effects analysis revealed that the difference between being in company ($M = 4.77$, $SD = 0.74$) or alone ($M = 4.44$, $SD = 0.87$) was significant only for the urban soundscapes, as predicted by Hypothesis 2b, $t(118) = 2.24$, $p < 0.05$. Contrary to our expectations concerning the natural soundscapes (Hypothesis 2a), the difference between being with a friend or alone was insignificant, $t(118) = 1.34$, $p = 0.18$.

The main effect of the demand for restoration condition (being attentionally fatigued or relaxed) was not statistically significant $F(1,116) = 0.91$, $p = 0.34$ nor was the interaction between company and demand for restoration, $F(1,116) = 0.88$, $p = 0.35$.

The interaction between demand for restoration (feeling attentionally fatigued or relaxed) and the restorative qualities of sonic environments was non-significant, marginally above conventional p-level, $F(1,116) = 3.69$, $p = 0.057$. Contrary to our assumptions, demand for restoration did not influence the restorative qualities for neither attentionally fatigued (Hypothesis 3a) nor relaxed participants (Hypothesis 3b).

Still, a significant three-way interaction (**Figure 2**) was found between the demand for restoration, company, and the restorative qualities of sonic environments, $F(1,116) = 4.31$, $p < 0.05$, $\eta_p^2 = 0.04$.

Relaxed participants preferred company over being alone both in the natural ($M = 5.56$, $SD = 0.54$ vs. $M = 5.47$, $SD = 0.63$) and in the urban soundscapes, ($M = 4.88$, $SD = 0.69$ vs. $M = 4.28$, $SD = 0.82$). However, the difference between being alone or with a friend was significant only for the urban sounds, $t(58) = 3.09$, $p < 0.01$. Attentionally fatigued participants favored company over solitude, but the differences were not significant for neither the natural soundscapes, $t(58) = 1.30$, $p = 0.21$ nor the urban soundscapes, $t(58) = 0.26$, $p = 0.80$.

Evaluation of the Imagined Soundwalks

As predicted in Hypothesis 4, we found a significant difference in the evaluation of the imagined soundwalks, $Z = -8.47$, $p < 0.001$. Participants preferred the walk in the natural soundscapes ($Mdn = 6.50$) over the walk in the urban soundscapes ($Mdn = 5.00$).

Sense of Security

Participants imagining their walks in urban soundscapes were hypothesized to report a greater sense of security than those imagining their walks in natural soundscapes (Hypothesis 5). A significant difference between the two was found, $Z = -6.90$, $p < 0.001$, but in the opposite manner: those imagining walks in

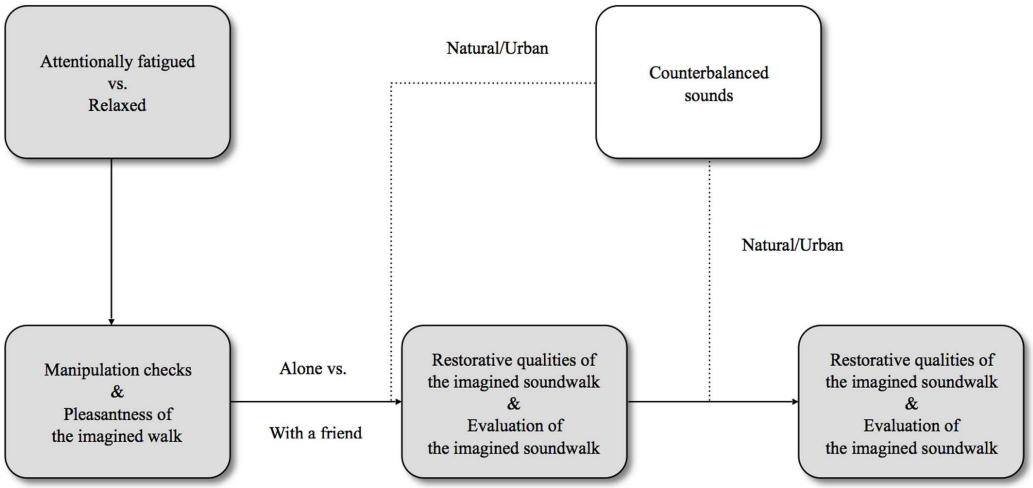


FIGURE 1 | An outline of the research procedure.

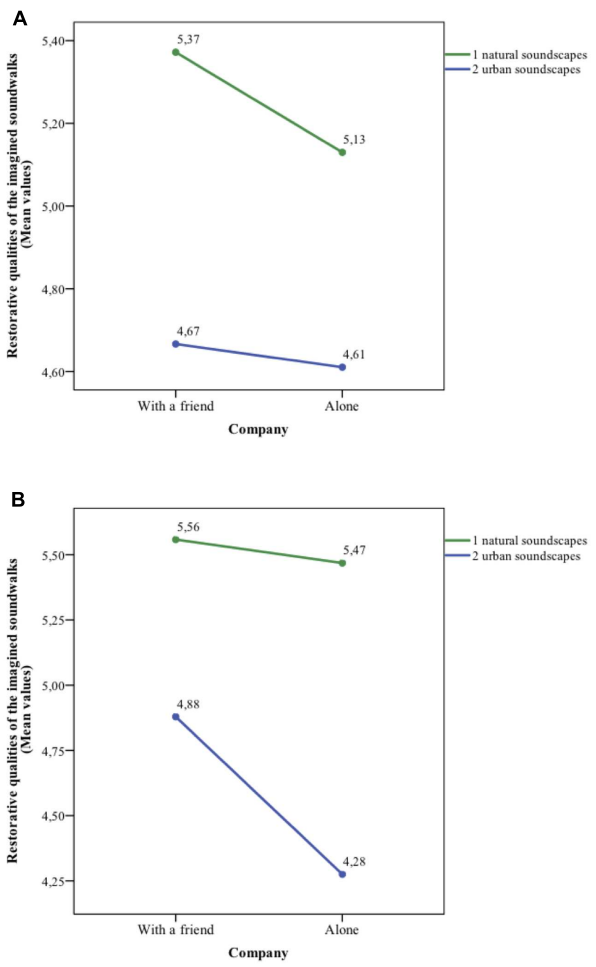


FIGURE 2 | Three-way interaction between the demand for restoration, company and restorative qualities of the imagined soundwalks for attentionally fatigued **(A)**, and relaxed **(B)** participants.

a natural sonic environment felt more secure ($Mdn = 6.00$ vs. $Mdn = 5.00$).

Additionally, participants were assumed to feel more secure in company no matter the sonic environments. According to our expectations (Hypothesis 6a), a significant difference in the assessment of security during the imaginary walk in natural soundscapes was found between those assigned to imagine company ($Mdn = 7.00$) and those assigned to imagine solitary walks ($Mdn = 6.00$), $U = 1302.00$, $p < 0.01$. However, contrary to our predictions (Hypothesis 6b), the appraisal of security in the urban soundscapes was the same ($Mdn = 5.00$) regardless of the company scenario, $U = 1574.50$, $p = 0.22$.

Effect of Company on Restorative Qualities as a Function of a Sense of Security

We examined two mediation models, one for the natural soundscapes (Hypothesis 7a) and one for the urban soundscapes (Hypothesis 7b), in which the relationship between company and the restorative qualities of sonic environments was mediated by a sense of security.

The standardized regression coefficient between company and a sense of security in the natural soundscapes was statistically significant, $b = -0.62$, $SE = 0.21$, $p < 0.01$, as was the standardized regression coefficient between a sense of security in the natural soundscapes and the restorative qualities of the natural sonic environment, $b = 0.17$, $SE = 0.05$, $p < 0.01$. Because two crucial assumptions of mediation were met (Kenny et al., 1998), further analyses were conducted: a bootstrapped estimation with 5000 samples yielded a significant indirect effect of company on natural soundscapes' restorative qualities through a sense of security in the natural sonic environment, $b = -0.10$, $SE = 0.04$, 95% CI $[-0.22, -0.03]$. The mediator accounted for more than half of the total effect, $P_M = 0.62$. Company was not a significant predictor of restorative qualities of the natural soundscapes after introducing the mediator to the model, $b = -0.06$, $SE = 0.12$, $p = 0.61$. As predicted (Hypothesis 7a),

the relationship between company and natural soundscapes' restorative qualities was mediated by a sense of security.

Conversely, for the urban soundscapes, company and a sense of security were not significantly related ($b = -0.31$, $SE = 0.26$, $p = 0.22$). Since the mediation assumptions were not met, further tests were not conducted (Baron and Kenny, 1986). Contrary to our expectations (Hypothesis 7b), the mediating effect of a sense of security in the urban sonic environment on the relationship between company and urban soundscapes' restorative qualities was not confirmed.

Effect of Company on Restorative Qualities as a Function of a Positive Evaluation of the Imagined Soundwalks

Because we were interested in the effect of a positive assessment on the perception of sounds, we also wanted to analyze the influence of a positive evaluation of the imagined walk in a given sonic environment (as an individual component extracted from the general evaluation of the imagined walk) on obtained results. For this reason, we tested two models, again one for the natural (Hypothesis 8a) and one for the urban soundscapes (Hypothesis 8b), in which the relationship between company and soundscapes' restorative qualities was mediated by a positive evaluation of the imagined walk in a given sonic environment.

For the natural soundscapes, the standardized regression coefficient between company and a positive evaluation of the imagined walk in the natural sonic environment was not statistically significant, $b = -0.18$, $SE = 0.14$, $p = 0.18$. As one of the basic mediation assumptions was not met (Baron and Kenny, 1986), further analyses were not conducted. Contrary to our predictions (Hypothesis 8a), the mediating effect of a positive evaluation of the imagined walk in the natural sonic environment on the relationship between company and natural soundscapes' restorative qualities was not confirmed.

By contrast, for the urban soundscapes, the standardized regression coefficient between company and urban soundscapes' restorative qualities was statistically significant, $b = -0.60$, $SE = 0.22$, $p < 0.01$, as was the standardized regression coefficient between a positive evaluation of the imagined walk in the urban soundscapes and the urban soundscapes' restorative qualities, $b = 0.34$, $SE = 0.05$, $p < 0.001$. A bootstrapped estimation with 5000 samples yielded a significant indirect effect of company on the restorative qualities of the urban sonic environment through a positive evaluation of the imagined walk in the urban soundscapes, $b = -0.21$, $SE = 0.08$, 95% CI [−0.38, −0.07]. The mediator could account for more than half of the total effect, $P_M = 0.62$. Company was no longer a significant predictor of urban soundscapes' restorative qualities, $b = -0.12$, $SE = 0.13$, $p = 0.35$. As expected (Hypothesis 8b), the relationship between company and urban soundscapes' restorative qualities was mediated by a positive evaluation of the imagined walk in the urban sonic environment.

Discussion

The main purpose of this study was to explore whether positively assessed urban soundscapes have comparable restorative qualities to natural sounds. We found that both positively assessed sonic environments were perceived as having different restorative qualities. An imaginary walk in the natural soundscapes, including birdsongs and water sounds, was evaluated as being more restorative than an imagined walk in the urban sonic environment, represented by sounds from places such as an old town or an amusement park. These results confirm previous findings about the restorative qualities of natural soundscapes, underlining the importance of greenery in urban surroundings.

It appears that the imagined walk did not change the perception of the urban sonic environment, which was still regarded as being less restorative than nature. It is possible that people do not imagine walking in an urban setting to be as restorative as walking in a natural surrounding. They walk in the city every day, commuting to work or school, often with a purpose and in a hurry. Daily routines are rarely associated with pleasure. A stroll in nature, however, could be perceived as something extraordinary, as a 'being away' experience with no need to rush and with the aim to relax.

The advantage of a natural sonic environment was also confirmed by a more positive evaluation of the imagined walk in nature. It is likely that perceived familiarity and representativeness of sounds affected these findings. We found that the most positively assessed natural recordings were perceived as more familiar and more representative of a given surrounding than the top five urban sounds. These results can be explained by the notion of comfort with the presented type of setting, described previously by Kaplan et al. (1993).

In Study 2, we also explored the roles of the demand for restoration and company. Participants evaluated restorative qualities of sonic environments more favorably when they were assigned to a company condition; however, the result was significant only for the urban soundscapes. Contrary to our expectations, demand for restoration did not influence perceived soundscapes' restorative qualities. Although we suspected that urban sounds could evoke hard fascination not conducive to restoration, this was not confirmed in the obtained results.

In an interaction between restorative qualities of sonic environments, company, and demand for restoration, relaxed participants generally favored being in company, but the difference was significant only in the urban soundscapes; attentionally fatigued participants also preferred company, but the differences between being alone or with a friend were not significant for both sonic environments. These findings suggest that the presence of a close friend is more important when one is in the urban setting.

It is probable that the sample of sounds used in the study partially accounted for the results. Most recordings represented urban environments conducive to meetings (e.g., a café) and visits by relaxed people (e.g., an amusement park). Our findings can therefore highlight the social aspect of an urban environment. Because the urban sounds were associated by participants of Study 1 with fun and social interaction, we can assume that participants preferred to share their experience with someone. It seems that loneliness in the urban environment is more disturbing (e.g., a few prefer be alone in a café). The importance of having company in the urban setting, represented by the urban

soundscapes, was reflected in mediation analysis. It turned out that a positive evaluation of the imagined walk in the urban sonic environment mediated the relationship between company and urban soundscapes' restorative qualities.

Company also increased the sense of security, but we found an interesting contradiction here. Although the urban soundscapes were perceived as less secure, it made no difference to participants whether they had company or not in urban sonic environment, but in the natural soundscapes, perceived as more secure, they preferred to be with someone. Evidently, company of others plays a different role in natural than in urban environments.

In consonance with previous research, in which visual stimuli were used (Staats and Hartig, 2004), mediation analysis confirmed the indirect effect of a sense of security on the relationship between company and the restorative qualities of natural sonic environment. These results might suggest that the urban environment, portrayed by urban sounds, is more predictable (participants know what to expect from the setting) and therefore participants are more likely to explore it alone.

GENERAL DISCUSSION

The combined findings from both studies suggest that natural sounds are perceived by people as being more restorative than urban recordings. This result holds even if only positively assessed urban sounds are used, and when additional factors, such as company or demand for restoration, are considered.

A possible explanation of these findings, which we have not discussed yet, is that natural and urban sounds differ in the extent to which they involve soft or hard fascination. According to Kaplan (1995), these two types of fascination coexist. Soft fascination, characterized by moderate intensity, is experienced in aesthetically pleasant environments, whereas hard fascination is much more intense and appears in more attentionally demanding environments (Heintzman, 2002), such as an exciting NBA match (Chow and Lau, 2015). In our study, natural sounds could have supported restoration by inducing soft fascination in contrast to urban sounds evoking hard fascination. While soft fascination restores concentration, and thus contributes to restoration to a greater extent than hard fascination (Reese and Myers, 2012), it is possible that our findings repeated this pattern. However, it seems that hard and soft fascination can also co-occur. In Study 1, for example, a concert recording, which was the most positively assessed sound of both environments, could have simultaneously induced hard fascination, because of its complexity, and soft fascination, because music is known for its ability to facilitate calm, tranquility and well-being (Krout, 2007; Labbé et al., 2007; Laukka, 2007; Linnemann et al., 2015).

The preference for natural soundscapes might also be explained by the psycho-evolutionary approach. It is believed that "for most of the millions of years during which our species evolved, humans coexisted in a close relationship with the natural environment. Therefore, most adaptations in the human organism, including those of the brain and related behavioral reactions, developed as an evolutionary response to needs imposed by this environment. In contrast, the history of human civilization is relatively short" (Hartig et al., 2011, p. 142). Hence, it is possible that despite the positive valence of urban areas represented by sounds associated with pleasant leisure activities, such as a concert, participants could nonetheless express an innate preference for nature represented by birdsongs and water-related recordings. Notably, because positively assessed urban sounds were mainly linked to recreation and entertainment, these results show that an urban soundscape cannot be equated to noise and its positive aspect should be more broadly acknowledged.

A few limitations of our studies should be mentioned. Because we wanted to depict different locations and use stimuli often used in other research, some of the sounds chosen for Study 1 could have been rated ambivalently or negatively (e.g., crows or road work), thus limiting the selection of potentially positive sounds. As a result, even though we made every effort to provide a variety of sounds, some of the urban facilities or natural habitats, which could have been assessed positively, were not represented (e.g., sports arena).

Moreover, the results obtained in Study 2 could have been partly affected by the role that imagined walking imposed on participants. Although in real life walking in natural surroundings (without additional activities) is a common form of recreation, in urban settings, especially ones similar to those presented in the study (e.g., an amusement park or café), the walk could be additionally associated with other activities accessible in such environments. Thus, for instance, the presence in an amusement park could be related to partaking in the entertainment offered in such places (e.g., taking a carousel ride), because it is rather unlikely to visit such a place just to stroll between attractions. As a result, the predetermined role of 'an observer' instead of the role of 'an active participant' could have resulted in a less positive evaluation of the restorative qualities of the urban soundscapes.

It should also be noted that our findings are limited to one modality (auditory), which may deprive us of some potentially relevant data. Therefore, in the future we would like to take a multimodal approach, which better mimics real-life experience.

In further research on restorative qualities of natural and urban environments, participants should be allowed to perform an attention-exhausting task prior to the beginning of the study. Future research could also investigate whether the presence of a real friend affects the results and whether differences in responses can be found between participants tested individually or in a group.

It is also worthwhile to mention the procedure used in Study 2. We based our scenarios and items on the ones described by Staats and Hartig (2004); however, it would be interesting to modify them, exploring in detail the impact of the evaluation of the environment on its restorative potential or personal preferences for activities and places associated with regeneration. Furthermore, items measuring restorative qualities of a given soundscape/surrounding could also include questions derived from other discovered factors of the ART, such as comfort with a given type of setting (Kaplan et al., 1993) or beauty (Ouellette et al., 2005; Herzog et al., 2010).

Additionally, individual differences between participants should be taken into account. The results found by Meagher (2016) suggest that not only the type of environment, but also personality traits, such as neuroticism, can influence psychological restoration. Future research should also examine the effects of stereotypes on the perception of the natural and urban sonic environments/settings and focus on the restorative qualities of urban surroundings.

Moreover, because a healthier urban biosphere, in which a place for coexistence of natural and artificial worlds would be found, seems to be potentially beneficial for urban residents, it is worthwhile to search for new, effective solutions that could have been implemented on macro (e.g., the WHO Healthy Cities project[1]) and micro scales (e.g., pocket gardens), to promote mental and physical heath within the urban surrounding. The idea that soundscapes, such as the murmur of a stream or birdsong, may change the perception of a given urban environment seems very appealing, as we have not yet fully discovered restorative qualities of sonic environments. Therefore, it would be interesting to further explore the way in which the relationship between sensory modalities (more than one) affects an environment's restorative qualities in a positive (what increases it) or negative (what decreases it) direction. It would also be worthwhile to concentrate more on the mutual penetration between natural and urban environments instead of viewing them as opposites.

CONCLUSION

In sum, our studies provided new knowledge about positively assessed urban sounds and their impact on the perceived restorative qualities of urban areas. Although the obtained results do not favor urban sonic environment, they emphasize the importance of natural soundscapes within an urban surrounding and the role of well-planed urbanized areas, which, with balanced artificial and natural settings, can be more beneficial to urban residents by promoting well-being, improving perceived quality of life and creating new spaces with potential for restoration within urban agglomerations.

[1] For more information about the WHO Healthy Cities project, see de Leeuw (2001).

ETHICS STATEMENT

These studies were carried out in accordance with the recommendations of the ethical guidelines of the faculty's ethics board with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

AUTHOR CONTRIBUTIONS

Research idea and study design: PK and KB. Data collection: PK. Data analysis and paper writing: PK and KB.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2017.01705/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Predicting the perceived restorative potential of bird sounds through acoustics and aesthetics



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Abstract

Some, but not all, bird sounds are associated with perceptions of restoration from stress and cognitive fatigue. The perceptual properties that might underpin these differences are understudied. In this online study, ratings of perceived restorative potential (PRP) and aesthetic properties of 50 bird sounds were provided by 174 residents of the United Kingdom. These were merged with data on objectively measured acoustic properties of the sounds. Regression analyses demonstrated that sound level, harmonics, and frequency, and perceptions of complexity, familiarity, and pattern, were significant predictors of PRP and cognitive and affective appraisals of bird sounds. These findings shed light on the structural and perceptual properties that may influence restorative potential of acoustic natural stimuli. Finally, through their potential associations with meaning, these findings highlight the importance of further study of semantic or meaning-based properties within the restorative environments literature.

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Keywords: restorative environments; soundscapes; acoustics; aesthetics; birdsong

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Spending time in or with non-threatening nature can generate cognitive and affective benefits, particularly after stress or mental fatigue (Berto, 2014; Hartig, Mitchell, de Vries, & Frumkin, 2014). Attention towards psychologically beneficial soundscapes in nature has grown in recent years, with birdsong as a common choice in such experimental studies, but there is limited understanding of why these sounds may afford positive outcomes. This paper examines how the perceptual properties of bird sounds relate to their perceived restorative potential, and cognitive and affective appraisals of the sounds.

Restorative Environments

Current theoretical frameworks of restorative environments focus on cognitive and affective processes as mechanisms responsible for attention restoration, recovery of positive mood, and reductions in arousal observed after exposure to natural environments (Kaplan, 1995; Kaplan & Kaplan, 1989; Ulrich, 1983; Ulrich et al., 1991). In attention restoration theory (ART; Kaplan, 1995; Kaplan & Kaplan, 1989), natural environments are proposed to aid the recovery of voluntary or directed attention, and subsequent improvements in mood, by engaging attention yet still offering opportunities for reflection. This may be achieved by certain qualities of person-environment transactions; that is, those that offer fascination or effortless attentional engagement, a sense of being away or escape, physical or perceptual extent, and compatibility with one's aims and desires.

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Ulrich's (1983; Ulrich et al., 1991) stress recovery theory (SRT) offers a different perspective, in which the benefits of nature following stress are framed in terms of affective appraisals of valence and arousal, as well as changes in physiological responses. SRT is sited in a psycho-evolutionary context, with aesthetic and semantic properties such as moderate levels of complexity, high levels of structure, even surface texture, the presence of water, and the absence of threat argued to contribute to environmental appraisals of positive valence and low arousal due to

their adaptive, psycho-evolutionary significance. Recently, researchers such as Joye and van den Berg (2011) have argued that there is relatively little evidence for primarily psycho-evolutionary perspectives on positive appraisals of potentially beneficial aspects of nature, instead suggesting that nature might be beneficial for attention because its perceptual properties tend to be easily processed by the visual system. However, these theoretical approaches consider experience of nature as a primarily visuo-spatial event.

Natural Sounds and Restoration: The Case for Bird Sounds

While receiving less attention than visuo-spatial experience in theoretical frameworks, the sounds of nature can be perceived and experienced as restorative. Bird sounds are almost always present in such soundscapes, which can reduce psychophysiological arousal faster, and improve mood to a greater extent, than certain sounds from the built or manmade environment (e.g., Alvarsson, Wiens, & Nilsson, 2010; Benfield, Taff, Newman, & Smyth, 2014; Jahncke, Eriksson, & Naula, 2015; Krzywicka & Byrka, 2017; Largo-Wight, O'Hara, & Chen, 2016; Medvedev, Shepherd, & Hautus, 2015; Payne, 2013; Ratcliffe, Gatersleben, & Sowden, 2013). These sounds may also improve self-reported motivation to work following fatigue (Jahncke, Hygge, Halin, Green, & Dimberg, 2011).

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Ratcliffe et al. (2013) observed bird sounds as the type of natural sound most commonly associated with perceived restoration (that is, self-reported perceptions of recovery from stress and mental fatigue), with affective appraisals of valence and arousal, and with cognitive appraisals that mirror two concepts from attention restoration theory – fascination and a sense of being away. Notably, these two factors from attention restoration theory do not rely on visuo-spatial judgments. The extent to which bird sounds were considered restorative, and the ways in which they were affectively and cognitively appraised in such ways, varied depending on the species mentioned by participants and the perceived acoustic and aesthetic properties of their sounds: the sounds of crows

and magpies were perceived to be unhelpful for restoration, for example, due to their "raucous" and "squawking" acoustic properties (Ratcliffe et al., 2013, p. 225).

As in studies that compare natural and man-made scenes, natural sounds, and particularly bird sounds, are often more positively affectively appraised than those from the built environment (e.g., Alvarsson et al., 2010; Anderson, Mulligan, Goodman, & Regen, 1983; Kariel, 1980; Kumar, Forster, Bailey, & Griffiths, 2008; Medvedev et al., 2015). Perceptions of pleasure also vary depending on the type of bird. For example, Björk (1985) noted that the sounds of songbirds were considered pleasant and sounds made by gulls less so, while Cox and Gaston (2015) identified songbirds as more preferred than calling, non-songbirds. Research in the visuo-spatial domain has forged ahead in recent years in understanding the specific perceptual properties that might contribute to restoration in natural environments (see Joye & van den Berg, 2011). However, there is little evidence about how variation in the perceived restorative potential of natural sounds (PRP; i.e., the judged likelihood that a stimulus can encourage restoration) might vary as a function of their perceptual properties; that is, acoustic properties and aesthetic appraisals. Since birds occur frequently in restorative soundscapes (e.g., Alvarsson et al., 2010; Benfield et al., 2014; Medvedev et al., 2015; Payne, 2013), they are a highly appropriate type of stimulus to use in order to examine relationships between specific acoustic and aesthetic properties of natural sounds and judgments of restorative value as measured via PRP, affective appraisals, and cognitive appraisals. By examining the relative contributions of these properties to such perceptions, it may be possible to better understand the mechanisms through which evaluations of the PRP of natural sounds can occur.

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The following two sections outline the main acoustic and aesthetic properties that may relate to PRP of bird sounds. Acoustic properties of sound level, harmonics, and frequency, and aesthetic properties of novelty, complexity, and pattern, are perceived as important in affective appraisals of bird sounds and perceptions of their restorative value (Ratcliffe et al., 2013). While there is a lack of research that quantitatively examines relationships between these properties and

such appraisals in the context of bird sounds, evidence for these potential relationships that draws on wider literature regarding acoustics and aesthetics is discussed below.

Acoustic Properties of Bird Sounds

Sound level. Existing research suggests a link between loud sound levels and appraisals of natural sounds as arousing, dominating, or symbolic of animal aggression (Björk, 1985; Morton, 1977; Tsai et al., 2010). Based on this, it is possible that loud bird sounds may be perceived as more arousing and negatively valenced than quiet bird sounds due to their associations with dominance and threat. However, understanding of relationships between bird sound level and PRP, as well as cognitive appraisals of fascination and being away, is limited.

Frequency. The frequency of a bird sound is related to its perceived pitch, and may also relate to affective appraisals and judgments of its restorative potential, although evidence for the direction of this relationship is mixed. Higher-frequency sounds, such as those made by songbirds, can be perceived as pleasant (Björk, 1985; Thorpe, 1961) but may be potentially arousing (Björk, 1985) due to associations with attack or distress calls (Halpern, Blake, & Hillenbrand, 1986; Kumar et al., 2008). However, Tsai et al. (2010) and Morton (1977) also link low-frequency animal sounds to arousing behaviors such as aggression or dominance. As such, there is mixed evidence for a directional relationship between frequency of bird sounds and affective appraisals, and as yet limited understanding of how frequency might relate to PRP or cognitive appraisals such as fascination and being away.

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Harmonics. The harmonicity of a sound relates to its acoustic periodicity or regularity; harmonic sounds are experienced as a clear signal, while unharmonic sounds are experienced as noise. Existing research on perceptions of natural or animal sounds suggests that low levels of sound harmonicity may be associated with negative valence (Björk, 1985; Juslin & Laukka, 2003; Tsai et al., 2010) and with arousal through association with low frequencies and dominant or aggressive animal behavior (Blumstein & Récapet, 2009; Fitch et al., 2002; Leinonen et al., 2003). As such,

harmonic bird sounds may be positively related to valence and negatively related to arousal ratings, although again, possible relationships with PRP and cognitive appraisals such as fascination and being away are unclear.

Aesthetic Properties of Bird Sounds

Familiarity. There is mixed evidence for associations between familiarity and restorative value of natural stimuli, with some research suggesting that the two are positively, although not always closely, related (e.g., Hartig & Staats, 2006; Purcell, Person, & Berto, 2001). Medvedev et al. (2015) linked perceived familiarity of bird sounds with its ability to generate stress recovery outcomes. In contrast, Ratcliffe et al. (2013) observed that the perceived novelty of bird sounds could provide feelings of escape, which is similar to the concept of being away outlined in attention restoration theory (ART; Kaplan, 1995; Kaplan & Kaplan, 1989), although perceptual novelty is not directly comparable to being away (Laumann, Gärling, & Stormark, 2001). Berlyne (1960, 1970) observed that both novelty of and familiarity with a stimulus have been associated with preference, pleasure, and interest. As such, the direction of any role of familiarity in PRP and affective and cognitive appraisals of bird sounds is unclear.

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Complexity. Moderate levels of environmental complexity may contribute to perceptions and/or experiences of nature as restorative (Kaplan & Kaplan, 1989; Ulrich, 1983), and it seems likely that the aesthetic property of complexity relates both to affective appraisals such as pleasure and arousal (see Berlyne, 1960, 1970) and cognitive appraisals such as fascination (Kaplan & Kaplan, 1989). However, there has been little study of such relationships in the context of restorative acoustic environments and stimuli. Ulrich (1983) discusses the role of visual complexity in preferences for and restorative experiences in nature, and while Berlyne's (1971) work on aesthetics does consider acoustic stimuli, his studies focused more on interest and affective appraisals than specifically on restoration from stress or cognitive fatigue. As such, there is a need to examine connections between complexity and evaluations such as PRP in the context of specific natural sounds.

Pattern. Patterned or structured environments can aid cognitive and affective restoration through affordances of safe, coherent spaces (Joye & van den Berg, 2011; Kaplan, 1995; Kaplan & Kaplan, 1989; Ulrich, 1983), whereas a moderate level of unpredictability or randomness among stimuli encourages interest and arousal (Berlyne, 1960). However, this focus on pattern versus randomness in restorative environments and aesthetics is centered on visual experiences. There is a lack of research on whether perceptions of pattern are related to evaluations of acoustic stimuli as potentially restorative, and in particular specific stimuli such as bird sounds that possess patterned structures in their own right (Thorpe, 1961).

The literature reviewed above suggests that certain acoustic and aesthetic properties of bird sounds may relate to perceptions of their restorative potential (PRP) in situations of stress and cognitive fatigue, affective appraisals of valence and arousal in response to the sounds, and cognitive appraisals of the sounds as generating fascination and a sense of being away, as noted in Ratcliffe et al. (2013). These affective and cognitive appraisals represent different constructs that are proposed to contribute to PRP within affectively- (Ulrich, 1983) and cognitively-focused (Kaplan & Kaplan, 1989) theories respectively. It is therefore important to examine each of these outcomes individually in order to understand how acoustic and aesthetic properties of bird sounds relate not just to overall PRP, but the appraisals that inform that PRP.

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Aims and Hypotheses

The present study sought to: a) quantify perceptions of bird sounds as potentially restorative, as measured via ratings of PRP and affective and cognitive appraisals of 50 10-second bird sound clips under states of imagined stress and mental fatigue; and b) examine how these ratings may be predicted by the objectively measured acoustic and subjectively measured aesthetic properties of the sounds; that is, their objectively measured sound level, harmonics, and frequency, and their subjectively measured familiarity, complexity, and pattern. Objective familiarity was also

captured by identifying country of origin of the bird sound; i.e., native to the UK (familiar) or Australia (novel). Based on existing literature, sound level and harmonics were expected to be negative and positive predictors of restorative perceptions, respectively. With regard to other predictor variables, the mixed nature of the evidence meant that directional hypotheses were not set, and potential relationships were explored.

The aim of this study was not to study in-depth the inter-relationships between ratings of the overall PRP of the bird sounds and affective and cognitive appraisals. Rather, the aim of this study was to establish whether, and to what extent, acoustic and aesthetic variables directly predict ratings of PRP, affective appraisals, and cognitive appraisals. This study follows the procedure put forward in Ratcliffe, Gatersleben, and Sowden (2016), in which qualitative data regarding associations with bird sounds were captured and related to quantitatively measured PRP scores. In this paper we reiterate the procedure undertaken but focus instead on the perceptual properties of acoustics and aesthetics, and their relationships to PRP and cognitive and affective appraisals of bird sounds.

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Method

Participants and Design

One hundred and seventy-four adult residents (123 female) of the United Kingdom took part in a predictive correlational study advertized as ‘responses to environmental sounds’. Participants were invited to take part online via adverts placed on social media, mailing lists, email-based snowball sampling, and posters located in London and the South East of England. All were aged between 18 and 68 (M = 35.52 years, SD = 13.22). No remuneration in cash or kind was provided in exchange for participation. Due to its non-sensitive nature the study was exempt from requiring ethical approval by the authors’ institutional ethics committee, but appropriate ethical guidelines were followed.

Materials and Stimuli

Dependent variables. Bird sounds were evaluated using three sets of measures, as follows:

Perceived restorative potential (PRP). The PRP of each bird sound was evaluated in terms of how helpful it would be for participants in need of recovery from cognitive fatigue and stress. The following vignette detailing such a scenario was provided, based on those used by Staats, Kieviet, and Hartig (2003) and Staats and Hartig (2004): "You've been working very hard recently. Now, after a long day, you really have had it. You have difficulty concentrating and are very irritable. To top it all off, you have had an upsetting argument with a friend and are feeling very stressed out about it. You sit down somewhere to take a break. To what extent would listening to this sound help you to recover in this scenario?" Participants rated agreement with the question per bird sound on a scale of 1 to 7 (not at all – completely). A more detailed discussion of this vignette and its development is contained in Ratcliffe et al., (2016).

Affective appraisals. The valence and arousal dimensions of the pictorial Self Assessment Manikin scale (SAM; Bradley & Lang, 1994) were used to measure affective appraisals in response to each sound. Each single-item scale measured affective response to a stimulus on a 9-point scale, from sad (1) to happy (9) and calm (1) to activated (9). Appraisals of affect and arousal have been implicated in perceptions and experiences of restorative environments, and particularly natural sounds (Benfield et al., 2014; Ratcliffe et al., 2013; Ulrich, 1983).

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Cognitive appraisals. Ratings of fascination and being away were measured using single items in response to each sound. The items used here are derived from items in scales in published papers. Items for being away ("Listening to this sound is an escape experience") and fascination ("This sound has fascinating qualities") were adapted from the highest-loading items on being away and fascination factors in Hartig, Kaiser, and Bowler's (1997) Perceived Restorativeness Scale (PRS). Each item was rated in terms of agreement on a scale from 0 (not at all) to 6 (completely), as in the PRS.

Independent variables. The aim of this study was to examine the absolute acoustic properties that might predict ratings of PRP and affective and cognitive appraisals. As such, objective measures of acoustic properties of bird sounds were utilized. These were computed using the bioacoustics software Praat (Boersma & Weenink, 2012). Self-report measures of aesthetic properties (familiarity, complexity, and pattern) were used due to the more subjective nature of these variables, particularly familiarity (see McDermott, 2012).

Objective properties. Sound level was measured via A-weighted equivalent sound pressure level in decibels (dB L_{Aeq}) as used by Björk (1985), with higher values corresponding to louder sounds. Since measurement of L_{Aeq} as heard by participants was not possible due to the online nature of this study, these data were gathered by proxy using a sound pressure level meter and closed-back headphones. Participants were asked to calibrate their computer's audio output to a certain level using a loudness matching task, in order to increase standardization of presentation of the audio clips and their sound intensity across participants. The matching task is described further in the Procedure section.

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Harmonics were measured using the harmonics-to-noise ratio (HNR), expressed in decibels (dB). This measure expresses the ratio of harmonic components of an acoustic signal to its noise components. HNR has been used with bioacoustic signals such as the human voice and dog barks, with low values representing harsh, rough sounds and high values representing smooth, clear sounds (Riede, Herzel, Brunnberg, & Tembrock, 2001).

Frequency was measured using the mean fundamental frequency (F_0) value, expressed in Hertz (Hz), for each bird sound, with increasing values corresponding to higher frequency. Björk (1985) reported that mean fundamental frequency was positively correlated with subjective perception of pitch (ρ = .95).

Country of origin of the bird sound (UK or Australia) was also included as an objective measure of familiarity, where 1 = UK and 2 = Australia. In a post-hoc check, participants rated UK

birds as significantly more familiar (M = 5.42, SD = .95) than Australian birds (M = 3.75, SD = 1.20), t (48) = 5.44, p < .001.

Subjective aesthetic appraisals. Familiarity, complexity, and pattern were measured using self-report semantic differential scales based on those used by Björk (1985). These were three items on a seven-point scale (1 – 7): very unfamiliar – very familiar; very simple – very complex; and very random – very patterned.

Stimuli. Fifty 10-second sound clips were used in the study, comprising sounds made by 25 common birds in the South East of England and 25 common birds in New South Wales in Australia. The sounds were presented in isolation with no species names or other information provided. The bird sounds were either songs or calls depending on the type of bird and its typical sound. Sound clips were collected from high-quality archives, with permission where necessary, and were evaluated for accuracy by two ornithologists. Sounds were randomly assigned to five groups of 10 sounds each (consisting of five UK bird sounds, and five Australian) using a random number generator corresponding to each sound clip. Via the online survey software, participants were randomly assigned to rate the sounds in one of these groups (participant Ns ranged from 30 to 39 per group), and the order of sound presentation was also randomized within each group.

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Procedure

In the online survey setting, participants provided electronic informed consent to participate in the study and for their data to be used in subsequent analyses. They calibrated their computer's sound output level via a loudness matching task. This involved listening to a test audio clip of a ballpoint pen being clicked up and down, and matching the perceived loudness of that audio clip to the clicking of a ballpoint pen of their own. For more details of this task, please see Ratcliffe et al. (2016; Appendix A). After this, participants completed a brief measure of demographic data and then rated 10 bird sounds on familiarity, complexity, pattern, affective and cognitive appraisals, PRP, and qualitative associations (see Ratcliffe et al., 2016). All measures

were completed for each bird sound before moving onto the next sound. Participants were asked to complete the measures for a test sound before beginning. At the end of the study, participants rated how comfortable they found the sound level of the audio clips (1 = very uncomfortable, 5 = very comfortable), before being thanked and debriefed online.

Results

Data Screening

Data from 25 participants were excluded due to procedural issues: 23 because participants rated the sounds as uncomfortably loud, and two due to physiological hearing difficulties. This resulted in data from 149 participants being retained for analysis.

Since not all participants rated all bird sounds, the possibility that scores on dependent variables varied by group was investigated. However, relevant intraclass correlation coefficients (ICC1) per dependent variable ranged from .01 to .03; i.e., only 1 to 3% of variance in the dependent variables was attributable to group membership. Schoemann, Rhemtulla, and Little (2014) indicate that in cases where less than 5% of variance is attributable to such a factor, multilevel modelling techniques may be inappropriate. As such, mean scores per bird sound on the DVs and subjective IVs were calculated and merged with objectively measured acoustic properties. Hierarchical multiple regression analyses were conducted using these data (i.e., individual bird sounds were treated as the unit of analyses, $N = 50$), with group assignment per sound (1 to 5) entered in the form of four dummy-coded predictors at Step 1; these variables accounted for a non-significant amount of variance (between <.01% and 4%, $ps > .05$) in each of the DVs.

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Multiple Regression Analyses

Five sets of hierarchical multiple linear regression analyses were conducted, with PRP, valence, arousal, fascination, and being away scores as respective dependent variables (DVs), and sound level, harmonics, frequency, country of origin, familiarity, complexity, and pattern as

independent variables (IVs). No multivariate outliers were identified, using Mahalanobis Distance values at 12 *df*, $p = .001$.

As shown in Table 1, frequency was significantly correlated with all DVs, and with two other IVs (familiarity and complexity). However, in multiple regression analyses (see Tables 2 to 6) where acoustic and aesthetic variables were entered together as predictors, the predictive role of frequency was consistently non-significant. This suggests that direct relationships between frequency and the dependent variables might be obscured by the presence of either familiarity or complexity, or both. As such, the regression analyses presented below outline steps in hierarchical regression models, with group membership entered in Step 1 (not shown in Tables for brevity), acoustic predictors in Step 2, and subjective aesthetic predictors entered thereafter (first individually in Steps 3a, b, and c, and then together in Step 3d), in order to better understand the unique predictive roles of each of these properties.

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As can also be seen in Table 1, valence and arousal scores were significantly negatively correlated. Given that valence and arousal as measured by the SAM are intended to be uncorrelated (Bradley & Lang, 1994), regression analyses with arousal/valence as DV included valence/arousal, respectively, as control variables in Step 1 alongside group membership. This was done in order to provide a more informative model of predictive relationships between acoustic and aesthetic properties and each affective appraisal, independent of variance associated with the other.

[TABLE 1 ABOUT HERE]

Regressing PRP score on acoustic and aesthetic variables. Together, acoustic and aesthetic properties predicted a significant 71% of variance in PRP score, over and above group membership. Step 2 indicated that approximately 43% of this variance was predicted by acoustic properties of the bird sounds. As shown in Table 2, bird sounds highest in PRP were those that were harmonic, high-frequency, and of a low sound level. Country of origin did not significantly predict PRP score.

In Steps 3a and 3b, familiarity and complexity were positive, significant predictors of PRP score, over and above acoustic properties. In Step 3c, pattern was not a significant predictor and its inclusion in the model did not significantly add to the explained variance in PRP score. However, in the full model listed under Step 3d, all aesthetic properties emerged as individually significant positive predictors of PRP, and explained a significant 28% of variance in PRP score.

The predictive role of frequency was reduced in the presence of both familiarity and complexity, but only became non-significant as a predictor when both aesthetic properties were present in the model, suggesting that indirect relationships between frequency and PRP score may be mediated through both familiarity and complexity.

[TABLE 2 ABOUT HERE]

Regressing valence on acoustic and aesthetic variables. Together, acoustic and aesthetic properties predicted a significant 29% of variance in valence score, over and above variance associated with group membership and arousal. Step 2 indicated that approximately 12% of this variance was predicted by acoustic properties of the bird sounds. As shown in Table 3, bird sounds rated as more likely to make participants happy were those that were high in frequency. Sound level, harmonics, and country of origin did not significantly predict valence score.

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In Steps 3a and 3c, familiarity and pattern were not significant predictors of valence score, over and above acoustic properties, and their addition to the models did not significantly explain any more variance in valence score. However, in Step 3b, complexity was a significant positive predictor. In the full model listed under Step 3d, both complexity and pattern emerged as individually significant positive predictors and explained a significant 17% of variance in valence score.

[TABLE 3 ABOUT HERE]

Regressing arousal on acoustic and aesthetic variables. Together, acoustic and aesthetic properties predicted a significant 20% of variance in arousal score, over and above variance

associated with group membership and valence. Step 2 indicated that approximately 14% of that variance was predicted by acoustic properties of the bird sounds. As shown in Table 2, bird sounds rated as more arousing were those that had high sound levels and low harmonicity. Country of origin and frequency did not significantly predict arousal score.

In Step 3a and 3b, familiarity and complexity were significant negative and positive predictors of arousal score, respectively, over and above acoustic properties. However, in Step 3c, pattern was not a significant predictor and addition of this variable to the model did not significantly explain any more variance in arousal score.

In the full model listed under Step 3d, the three aesthetic variables explained a significant 6% of variance in arousal score, but complexity emerged as the only significant, positive aesthetic predictor. In the presence of all three aesthetic variables together, harmonics became a non-significant predictor, suggesting a possible mediating role for a combination of aesthetic properties in the relationship between harmonics and arousal.

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[TABLE 4 ABOUT HERE]

Regressing fascination on acoustic and aesthetic variables. Together, acoustic and aesthetic properties predicted a significant 74% of variance in fascination score, over and above group membership. Step 2 indicated that approximately 23% of the variance in fascination was predicted by acoustic properties of the bird sounds. Harmonics emerged as a significant, positive predictor of fascination score, while sound level, frequency, and country of origin were not significant predictors.

In Step 3a, familiarity was not a significant predictor of fascination score, over and above acoustic properties, and addition of this variable to the model did not significantly increase explained variance in fascination score. However, in Steps 3b and 3c, complexity emerged as a significant positive predictor and pattern as a significant negative predictor of fascination. In the presence of these aesthetic variables, sound level became a significant negative predictor.

In the full model shown under Step 3d, complexity and harmonics remained as significant positive predictors, while pattern and sound level became non-significant. Altogether, the three aesthetic variables explained a significant 51% of variance in fascination score.

[TABLE 5 ABOUT HERE]

Regressing being away on acoustic and aesthetic variables. Together, acoustic and aesthetic properties predicted a significant 70% of variance in being away score, over and above group membership. Approximately 40% of that variance was predicted by acoustic properties of the bird sounds. Harmonics and frequency were significant, positive predictors, and sound level was a significant negative predictor of being away. Country of origin was not a significant predictor.

In Steps 3a and 3c, familiarity and pattern were not significant predictors of being away score, over and above acoustic properties, and inclusion of these variables did not result in a significant change to the amount of variance explained by the model. In Step 3b, complexity emerged as a significant positive predictor of being away. Frequency became a non-significant predictor in the presence of complexity, suggesting a potential mediating effect of this aesthetic variable on the relationship between frequency and being away. In the full model shown in Step 3d, harmonics was the only remaining significant acoustic predictor, while familiarity, complexity, and pattern were significant aesthetic predictors. Altogether, the three aesthetic variables explained a significant 30% of variance in being away score.

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[TABLE 6 ABOUT HERE]

Discussion

Acoustic properties of sound level, frequency, and harmonics, and aesthetic properties of familiarity, pattern, and complexity, were significant predictors of perceptions of bird sounds as potentially restorative, positively valenced, and generating a sense of being away. To a lesser extent, these variables also predicted perceptions of arousal and fascination. Together, acoustic and aesthetic factors predicted 70 - 74% of variance in PRP, fascination, and being away scores, and 20

- 29% of variance in arousal and valence scores. Potential explanations for the low level of explained variance in arousal include: a limited range of certain acoustic properties such as sound level utilized in this study; possible roles of other unmeasured acoustic or aesthetic properties such as sound brightness, as well as semantic associations with the sounds; or the unexplored possibility of curvilinear relationships between arousal and acoustic and aesthetic properties. For example, natural sounds with either very low or very high frequencies may be more arousing than those with more moderate frequencies, due to associations between sounds in these frequency bands and threat or distress signals (Björk, 1985; Halpern et al., 1986; Kumar et al., 2008; Morton, 1977; Tsai et al., 2010).

Hierarchical regression analyses also revealed that inclusion of subjective aesthetic properties of complexity and familiarity within the models reduced the predictive roles of acoustic properties such as frequency and harmonics. This provides an initial indication that subjective evaluations of the way bird sounds are structured may mediate relationships between the objective acoustic properties of these sounds and ratings of their perceived restorative potential.

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Dependent Variables

Acoustic properties explained a total of 40 to 45% of variance in PRP and being away score, 23% of variance in fascination score, 14% of variance in arousal score (when cleared of variance associated with valence), and 12% of variance in valence score (when cleared of variance associated with arousal). This suggests that acoustic properties of sound level, harmonics, and frequency may be most relevant to measures that capture both cognitive and affective appraisals, such as PRP score. In contrast, subjective aesthetic properties explained a total of 51% of variance in fascination score, 25 to 30% of variance in PRP and being away scores, 17% of variance in valence score, and only 6% of variance in arousal score. As such, aesthetic properties appear more relevant to measures that focus on cognitive appraisals.

PRP, valence, fascination, and being away scores were highly positively correlated (see Table 1), but arousal score was more highly correlated with PRP and valence scores than with cognitive variables of fascination and being away. Despite the strong correlations between PRP, valence, fascination, and being away, conducting separate regression analyses per dependent variables was important given that affective appraisals are not strongly integrated into ART constructs, and similarly cognitive processes are not emphasized in SRT. Therefore, this study examined whether acoustic and aesthetic properties might present different patterns of prediction for each of these dependent variables, and indeed despite being strongly correlated with PRP, valence, and being away scores, fascination did show a different pattern of prediction by acoustic and aesthetic variables, which may relate to its greater emphasis on cognitive rather than affective appraisal of stimuli.

Despite the differences in regression models observed for the dependent variables, we acknowledge the presence of strong positive correlations between several of these variables. Positive correlations between PRP and valence, and negative correlations between valence and arousal, may be explained by the need for restoration elicited in the stress and cognitive fatigue vignette provided to participants; for example, preference for natural environments is known to be influenced by need for restoration (Hartig & Staats, 2006; van den Berg, Koole, & van der Wulp, 2003), and participants in this study may have rated certain bird sounds as positively valenced (a similar concept to preference) because they also perceived them as high in restorative potential (and, conversely, low on arousal).

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Correlations between PRP, fascination, and being away scores are not unexpected given that the latter two constructs are proposed by ART to be constituent processes within the wider experience of attention restoration. Correlations between these variables and valence are also to be expected given that, in their initial presentation of ART, Kaplan and Kaplan (1989, p. 189) suggest that “a preferred environment is thus more likely to be a restorative environment” (although notably

this proposes a different direction of relationship to that discussed by Hartig & Staats, 2006, and van den Berg et al., 2003).

Acoustics

Acoustic properties of sound level, frequency, and harmonics were significant predictors of PRP and being away scores. Harmonics and sound level were significant predictors of arousal, while harmonics alone significantly predicted fascination and frequency alone predicted valence.

Sound level. These findings confirm existing evidence that sound level may primarily be associated with appraisals of affective arousal in response to natural sounds (Björk, 1985; Tsai et al., 2010), and extends this by linking it to perceptions of restorative potential, supporting findings from Ratcliffe et al. (2013) that loud bird sounds were not considered restorative.

Harmonics. The broadly consistent relationship between harmonics and all dependent variables bar valence supports evidence suggesting that harmonic sounds are preferred over those that are unharmonic or evaluated as rough-sounding (e.g., Berlyne, 1971; Kumar et al., 2008). The fact that valence was not significantly predicted by harmonics may be related to shared variance between valence and arousal, and suggests that harmonicity may act more on affective appraisals of arousal than pleasure. This, again, corresponds with links between unharmonic animals sounds and their threatening semantic value (Tsai et al., 2010). The fact that harmonic sounds possess inherent structure may also explain their positive prediction of attention restoration constructs of fascination and being away, in that they can be easily processed.

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Frequency. When considered separately from aesthetic variables, frequency was a positive predictor of PRP, valence, and being away scores. This supports previous findings of associations between pleasantness and higher-frequency natural sounds, and especially bird sounds (Björk, 1985; Thorpe, 1961). In contrast to findings by Björk (1985) that such sounds relate positively to arousal, however, this study found no such predictive relationship for frequency. Frequency was

also not implicated in ratings of fascination; rather, aesthetic variables bore greater relation to this outcome, and are discussed below.

Aesthetics

Subjective sound familiarity was a significant predictor of PRP, arousal, and being away scores. Complexity was a significant predictor of all dependent variables. Pattern was a significant predictor of PRP, valence, fascination, and being away scores, although in the case of fascination pattern was a negative, rather than positive, predictor.

Familiarity. All dependent variables, with the exception of fascination, were significantly predicted by subjective familiarity ratings. In the case of PRP and being away scores, familiarity was a positive predictor, while it was a negative predictor of arousal. In Ratcliffe et al. (2013), some participants felt that the novelty of certain bird sounds would be helpful for restoration, but findings from this study contradict this position and suggest that, when measured quantitatively, familiar bird sounds are perceived as potentially restorative, low in arousal, and generating a sense of being away. Notably, familiarity was not predictive of valence score, which contradicts findings from literature on music perception, where familiarity has been found to be related to intensity of emotional responses such as liking (McDermott, 2012). Participants' imagined need for restoration in this study may have made ratings of familiarity more relevant for arousal score than for valence.

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Kaplan and Kaplan (1989) suggest that being away from one's everyday concerns can aid recovery from cognitive fatigue, but Laumann et al. (2001) note that being among novel stimuli is conceptually different from achieving psychological escape or awayness. In the context of this study, the observation that familiar birds are perceived to be more restorative than novel bird sounds suggests that listeners may not need to travel far to find this kind of psychological escape. It is also notable that this relationship was based on perceived, rather than absolute, novelty, since country of origin was not a significant predictor of any of the dependent variables, despite being significantly related itself to perceived familiarity (see Table 1). Future studies may wish to investigate whether

explicitly stating whether or not a bird is native influences restorative perceptions of its sound, as well as exploring whether reciprocal relationships between familiarity and restorative potential might be found among a sample of Australian participants.

Complexity. All dependent variables were significantly and positively predicted by complexity ratings. Complex bird sounds were rated as higher in PRP, more pleasant, more fascinating, and generated higher being away ratings than bird sounds that were simple, yet they were also rated as more arousing. This extends existing findings that (moderately) complex visuo-spatial elements of nature can also be perceived as restorative (Kaplan & Kaplan, 1989; Ulrich, 1983). An explanation that balances positive relationships between complexity and both PRP and arousal (which are theoretically negatively correlated) might be that bird sounds offer a moderate range of complexity that is neither over- nor under-stimulating. This study also demonstrates that complexity is predictive of a sense of being away, which might be related to the distraction offered by complex, rather than simple, bird sounds.

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Pattern. Pattern was a significant, positive predictor of PRP, valence, and being away scores. It was also a significant negative predictor of fascination when added into the regression model alone. Ulrich (1983) theorized that structured natural environments are more likely to be restorative than chaotic ones due to their ease of navigability, and similarly Kaplan and Kaplan (1989) proposed that an environment that is coherent will also be easier to process, and is therefore more likely to be restorative. This perspective is echoed in Joye and van den Berg's (2011) processing fluency account (PFA). Findings regarding pattern in this study suggest that these theoretical constructs may be applicable to bird sounds as well as visuo-spatial stimuli.

The observation that more patterned bird sounds were rated as less fascinating may relate to the proposed distinction between 'soft' and 'hard' types of fascination (Kaplan & Kaplan, 1989); i.e., more patterned bird sounds may be more moderately or 'softly' fascinating than those that are less predictable and therefore engage more of one's attention. It is notable that pattern was

not significantly related to arousal, of which familiarity was a better aesthetic predictor. A speculative explanation for the predictive role of pattern in ratings of being away may be that patterned bird sounds required less focus and thereby provided greater opportunity to escape the need for concentration, in comparison to more unpredictable bird sounds.

Aesthetic properties as potential mediators of relationships between acoustics and perceptions of bird sounds. When regressing PRP and being away score on acoustic and aesthetic variables together, the predictive role of frequency was reduced in the presence of familiarity and complexity. A similar reduction was found in relation to sound harmonics as a predictor of arousal, in the presence of all three aesthetic properties. Such effects were not hypothesized based on the paucity of research on this topic in the context of restorative environments. However, these findings suggest potential mediating effects of complexity, pattern, and/or familiarity on relationships between certain acoustic properties of bird sounds and judgments regarding their perceived restorativeness. Future research involving a larger sample of bird sounds may wish to examine this via formal mediated regression analyses.

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When fascination was regressed on acoustic and aesthetic variables, sound level only became a significant negative predictor when in the presence of complexity or pattern variables alone. Pattern was moderately negatively correlated with sound level (see Table 1), and as such inclusion in the model may have revealed a unique contribution of this acoustic variable to fascination; despite this, the predictive role was not strong enough to remain significant in the full model.

Study Limitations

Contributions of semantic and individual differences to ratings. The regression models above predicted between 20 and 74% of variance in PRP, affective appraisal, and cognitive appraisal variables. However, given that scores were averaged per bird rather than per participant, some data regarding individual participant responses to the bird sounds is inevitably lost. This may be of

particular relevance to the familiarity variable. Additionally, use of the 50 bird sounds as units of analysis meant that sample sizes per regression were small ($N = 50$).

Furthermore, associations with bird sounds were not captured in this study (although see Ratcliffe et al., 2016, for a treatment on this topic) and may contribute to unexplained variance. As other authors on perceptions of and responses to nature have noted (e.g., Cox & Gaston, 2015; Kumar et al., 2008; Pretty, 2004; Ulrich, 1983), the semantic value of such stimuli is likely to contribute to perceptions of their restorative value. A speculative interpretation of this study's findings is that certain acoustic properties, such as sound level and harmonics, may be associated with the intention behind the sound, and particularly with aggressive or threatening behavior on the part of the animal making the sound (see Morton, 1977; Tsai et al., 2010). Individuals may also have personal or cultural associations with bird sounds independent of their perceptual properties; for example, certain birds may be associated with memories of a place or time (e.g., Mynott, 2009).

Assumed need for restoration through use of vignettes. This study utilized a vignette that detailed the need for affective and attentional restoration (PRP), requiring participants to rate the likelihood that each bird sound would help them recover from such a scenario as well as provide ratings of affective and cognitive appraisals of each sound. The vignette approach has been utilized in previous restorative environments literature, in which such a scenario was rated as familiar and conceivable (Staats et al., 2003; Staats & Hartig, 2004). The scenario used in this study was rated as less familiar to participants than that used in the work of Staats and colleagues, but it was similarly conceivable (see Ratcliffe et al., 2016, for details). As such, it is presented as a valid and reliable way of subjectively assessing the perceived restorative potential of a range of brief auditory stimuli, particularly since other subjective measures of restorative potential focus on visuo-spatial experience (e.g., PRS, Hartig et al., 1997) or broader soundscapes (see Payne, 2013).

This study examined multiple facets of restorative perceptions of bird sounds by measuring a set of dependent variables known to relate to perceived restorative potential of natural

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environments, and affective and cognitive appraisals of such environments. These variables were identified by Ratcliffe et al. (2013) as being particularly relevant to evaluations of bird sounds as potentially restorative. Single-item measures were deemed most appropriate so as not to exhaust participants during the procedure. However, it is acknowledged that this type of dependent variable may lead to a lack of reliability. Future research may wish to induce affective and attentional fatigue, rather than ask participants to imagine it, and to measure responses to a smaller range of bird sounds using multiple-item instruments measuring subjective restorative and/or affective outcomes; e.g., the Restoration Outcome Scale (ROS; Korpela, Ylén, Tyrväinen, & Silvennoinen, 2008) as well as performance and/or psychophysiological measures.

Online nature of the study. Given that this study was conducted in an online setting, certain factors were beyond experimental control; namely, the equipment that participants used to listen to the sounds and the acoustic setting that they conducted the study in. Participants were asked to participate in the study at a time when they were free from interruptions in order to minimize interference from extraneous stimuli. Participants were asked to familiarize themselves with the questions through use of a practice task, and to complete a short audio calibration task before listening to the sounds in order to maintain approximately the same sound level across the sample. However, we acknowledge that this calibration process has limitations. Participants compared the loudness of an audio recording of a ballpoint pen to the sound made by a pen of their own, and the validity of this procedure may have been affected by lack of uniform loudness between participants' pens. Future research may benefit from being conducted in a laboratory using standardized equipment and headphones in order to further control for error variance associated with differences in procedure.

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Sounds isolated from the wider soundscape. The purpose of this study was to examine the relative contributions of acoustic and aesthetic properties of bird sounds to ratings of their perceived restorative potential, in order to better understand the perceptual mechanisms through which

cognitive, affective, and restorative appraisals of these common stimuli might occur. In order to do this accurately, it was necessary to isolate the bird sounds from their acoustic context as far as possible. This was done by presenting the bird sounds in short clips, free of extraneous sounds made by other birds and animals, water, and wind. Ratings and measurements of aesthetic and acoustic properties were therefore made in response to the bird sounds alone rather than any accompanying sounds. However, it is acknowledged that bird sounds are rarely heard in isolation in the natural world, and are usually experienced in the context of a wider natural soundscape. Therefore, this study does not seek to extend its conclusions to the predictive role of acoustics and aesthetics in the perceived restorative potential of other natural sounds, soundscapes, or environments; rather, these findings serve as a first step in showing how acoustics and aesthetics play a role in restorative perceptions of bird sounds.

Conclusions and Implications

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This study explored predictive relationships between acoustic and aesthetic properties and restorative perceptions relating to 50 bird sounds. Through an online study conducted with 174 participants, a number of acoustic and aesthetic properties were found to significantly predict ratings of variables related to restoration in the context of British and Australian bird sounds; that is, their perceived restorative potential (PRP), and ratings of valence, arousal, fascination, and being away. Harmonics, sound level, frequency, familiarity, complexity, and pattern each had significant predictive roles, depending on the DV in question.

Each bird sound is a product of a combination of acoustic and aesthetic properties that are not, in practice, always easily dissociable from each other (as shown by the possible mediating relationships between acoustic and aesthetic variables identified in this study). However, different patterns of prediction were especially apparent between arousal and fascination. Acoustic properties were more relevant for the former, while aesthetic properties were more relevant for the latter. As such, researchers studying cognitive responses to natural sounds may wish to attend to aesthetic

properties of complexity and pattern when choosing stimuli, whereas those with more emphasis on affective responses may wish to prioritise acoustic properties and familiarity when making such choices. For an exhaustive ranking of the 50 bird sounds according to their PRP scores, please see Ratcliffe et al. (2016), which may be of use to researchers who wish to choose bird sounds likely to be perceived as restorative in their work.

Building on findings from Ratcliffe et al. (2016) regarding associations with bird sounds and their links to restorative perceptions, the results presented here indicate that certain perceptual and aesthetic properties of bird sounds are also related to how restorative they are considered to be and how they are cognitively and affectively appraised. Given that the majority of literature in the field has focused on visuo-spatial experience of nature, this study provides novel insights into restorative nature as experienced through sound, and specifically a type of sound that individuals perceive to be particularly restorative (Ratcliffe et al., 2013). In so doing it highlights the need for further study of the role of perceptual properties of auditory environments in restoration as well as those that are experienced visuo-spatially. Such research may be of benefit not only to academic environmental psychologists, but also conservation practitioners who wish to encourage positive experiences in natural places through the different sensory experiences afforded therein.

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Table 1. Matrix of correlations between acoustic and aesthetic properties, cognitive and affective appraisals, and perceived restorative potential (PRP) per bird sound.

Variables	PRP	Valence	Arousal	Fascination	Being away	Sound level (dB L_{Aeq})	Harmonics (HNR Hz)	Frequency (Hz)	Country of origin	Familiarity	Complexity	Pattern
Valence	.95***											
Arousal	-.78***	-.71***										
Fascination	.87***	.84***	-.50***									
Being away	.97***	.96***	-.68***	.92***								
Sound level (dB L_{Aeq})	-0.25*	-0.20	0.45***	-0.12	-0.19							
Harmonics (HNR Hz)	0.43***	0.46***	-0.36**	0.39**	0.46***	0.27*						
Frequency (Hz)	0.55***	0.59***	-0.34**	0.46***	0.55***	-0.14	0.31*					
Country of origin	-0.20	-0.21	0.18	-0.08	-0.16	0.12	0.08	-0.09				
Familiarity	0.45***	0.47***	-0.46***	0.56	0.37**	-0.26*	-0.05	0.30**	-0.62***			
Complexity	0.46***	0.43***	-0.05	0.74***	0.55***	0.06	0.13	0.34***	-0.01	-0.03		
Pattern	0.22	0.28*	-0.35**	-0.09	0.15	-0.22*	0.14	0.05	-0.20	0.29*	-0.50***	
Min.	1.50	3.52	3.19	2.40	1.63	47.00	-.23	294.35	-	1.90	3.00	3.16
Max.	5.26	7.52	5.62	5.28	5.13	62.70	28.00	6336.53	-	6.71	6.24	6.00
Mean	3.29	5.87	4.44	4.09	3.54	55.48	13.28	2922.00	-	4.59	4.62	4.60

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Standard deviation	1.04	1.02	0.56	0.72	0.89	3.93	7.18	1708.67	-	1.36	0.86	0.75

N = 50. * $p < .05$, ** $p < .01$, *** $p < .001$. Country of origin = categorical variable (1 = UK, 2 = Australia). Ratings scales: PRP = 1 (not at all) to 7 (completely); valence and arousal = 1 (sad/calm) to 9 (happy/activated); fascination and being away = 0 (not at all) to 6 (completely); familiarity, complexity, and pattern = 1 (very unfamiliar/simple/random) to 7 (very familiar/complex/patterned).

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Table 2. Hierarchical linear regression statistics for predictor variables (acoustic and aesthetic properties) with perceived restorative potential (PRP) as dependent variable.

	IV	*t*	*B*	*SE B*	*β*
Step 2	Sound level	-2.60**	-.08	.03	-.31
$R^2_{Adj}Chg$ = .43	Harmonics	3.35**	.06	.02	.41
FChg (4, 41) = 9.90***	Frequency	2.92**	< .001	< .001	.35
	Country	-1.50 ^{ns}	-.34	.23	-.16
Step 3a	Sound level	-2.30*	-.07	.03	-.26
$R^2_{Adj}Chg$ = .06	Harmonics	3.69***	.06	.02	.43
FChg (1, 40) = 5.96*	Frequency	2.21*	< .001	< .001	.27
	Country	.25 ^{ns}	.07	.27	.03
	Familiarity	2.44*	.26	.11	.34
Step 3b	Sound level	-3.17*	-.09	.03	-.33
$R^2_{Adj}Chg$ = .12	Harmonics	3.70***	.06	.02	.41
FChg (1, 40) = 11.70***	Frequency	2.04*	< .001	< .001	.23
	Country	-1.71^{ns}	-.34	.20	-.17
	Complexity	3.42***	.44	.13	.36
Step 3c	Sound level	-2.37*	-.08	.03	-.30
$R^2_{Adj}Chg$ < .001	Harmonics	3.14**	.06	.02	.41
FChg (1,40) = .02^{ns}	Frequency	2.88**	< .001	< .001	.36
	Country	-1.41^{ns}	-.33	.23	-.16
	Pattern	.15^{ns}	.03	.17	.02
Step 3d	Sound level	-2.02*	-.05	.02	-.18
$R^2_{Adj}Chg$ = .28	Harmonics	3.55***	.05	.01	.33
FChg (3, 38) = 14.37***	Frequency	1.00^{ns}	< .001	< .001	.10
	Country	1.17^{ns}	.24	.21	.12
	Familiarity	3.61***	.28	.08	.39
	Complexity	5.70***	.72	.13	.60
	Pattern	2.97**	.44	.15	.32

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N = 50. *** $p \leq .001$, ** $p \leq .01$, * $p \leq .05$, ^{ns} Not significant. Country = categorical variable (1 = UK, 2 = Australia). Ratings scales: PRP = 1 (not at all) to 7 (completely); familiarity, complexity, and pattern = 1 (very unfamiliar/simple/random) to 7 (very familiar/complex/patterned).

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Table 3. Hierarchical linear regression statistics and significance values for predictor variables (acoustic and aesthetic properties) with valence score as dependent variable.

	IV	*t*	*B*	*SE B*	*β*
Step 2	Sound level	.96 ^{ns}	.03	.03	.12
$R^2_{Adj}Chg$ = .12	Harmonics	.85 ^{ns}	.01	.02	.10
FChg (4, 40) = 4.63**	Frequency	3.32**	< .001	< .001	.32
	Country	-1.02 ^{ns}	-.18	.18	-.09
Step 3a	Sound level	.74 ^{ns}	.02	.03	.09
$R^2_{Adj}Chg$ < .001	Harmonics	1.16 ^{ns}	.02	.02	.14
FChg (1, 39) = 1.11 ^{ns}	Frequency	2.92**	< .001	< .001	.29
	Country	-.19 ^{ns}	-.04	.22	-.02
	Familiarity	1.05 ^{ns}	.10	.10	.14
Step 3b	Sound level	1.01 ^{ns}	.03	.03	.11
$R^2_{Adj}Chg$ = .09	Harmonics	.83 ^{ns}	.01	.01	.08
FChg (1, 39) = 14.72***	Frequency	2.45*	< .001	< .001	.21
	Country	-1.18 ^{ns}	-.18	.15	-.09
	Complexity	3.84***	.37	.10	.31
Step 3c	Sound level	.99 ^{ns}	.03	.03	.12
$R^2_{Adj}Chg$ < .001	Harmonics	.78 ^{ns}	.01	.02	.09
FChg (1, 39) = .07 ^{ns}	Frequency	3.28*	< .001	< .001	.32
	Country	-.94 ^{ns}	-.17	.18	-.09
	Pattern	.27 ^{ns}	.04	.13	.03
Step 3d	Sound level	1.56 ^{ns}	.04	.02	.14
$R^2_{Adj}Chg$ = .17	Harmonics	.79 ^{ns}	.01	.01	.07
FChg (3, 37) = 13.16***	Frequency	2.01*	< .001	< .001	.16
	Country	.74 ^{ns}	.12	.16	.06
	Familiarity	1.96 ^{ns}	.14	.07	.19
	Complexity	6.11***	.61	.10	.51
	Pattern	3.69***	.43	.12	.32

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N = 50. *** $p \leq .001$, ** $p \leq .01$, * $p \leq .05$, ns Not significant. Country = categorical variable (1 = UK, 2 = Australia). Ratings scales: valence = 1 (sad) to 9 (happy); familiarity, complexity, and pattern = 1 (very unfamiliar/simple/random) to 7 (very familiar/complex/patterned). Arousal was controlled for along with group membership in Step 1.

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Table 4. Hierarchical linear regression statistics and significance values for predictor variables (acoustic and aesthetic properties) with arousal score as dependent variable.

	IV	*t*	*B*	*SE B*	*β*
Step 2	Sound level	4.77***	.06	.01	.44
$R^2_{Adj}Chg$ = .14	Harmonics	-2.54*	-.02	.01	-.27
FChg (4, 40) = 5.95***	Frequency	1.10 ^{ns}	< .001	< .001	.11
	Country	.51 ^{ns}	.05	.09	.04
Step 3a	Sound level	4.88***	.06	.01	.43
$R^2_{Adj}Chg$ = .03	Harmonics	-3.12**	-.03	.01	-.32
FChg (1, 39) = 4.70*	Frequency	1.38 ^{ns}	< .001	< .001	.14
	Country	-.83 ^{ns}	-.09	.11	-.08
	Familiarity	-2.17*	-.10	-.05	-.25
Step 3b	Sound level	4.45***	.06	.01	.40
$R^2_{Adj}Chg$ = .04	Harmonics	-2.20*	-.02	.01	-.23
FChg (1, 39) = 6.38*	Frequency	.86 ^{ns}	< .001	< .001	.08
	Country	.24 ^{ns}	.02	.09	.02
	Complexity	2.53*	.15	.06	.23
Step 3c	Sound level	4.36***	.06	.01	.43
$R^2_{Adj}Chg$ < .001	Harmonics	-2.37*	-.02	.01	-.26
FChg (1, 39) = .26 ^{ns}	Frequency	.99 ^{ns}	< .001	< .001	.10
	Country	.40 ^{ns}	.04	.10	.04
	Pattern	-.51 ^{ns}	-.04	.07	-.05
Step 3d	Sound level	4.85***	-.39	.01	.43
$R^2_{Adj}Chg$ = .06	Harmonics	-2.65 ^{ns}	-.02	.01	-.27
FChg (3, 37) = 3.70*	Frequency	1.25 ^{ns}	< .001	< .001	.12
	Country	-.29 ^{ns}	-.03	.11	-.03
	Familiarity	-1.13 ^{ns}	-.06	.05	-.14
	Complexity	2.43*	.21	.09	.32
	Pattern	1.56 ^{ns}	.14	.09	.18

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N = 50. *** $p \leq .001$, ** $p \leq .01$, * $p \leq .05$, ^{ns} Not significant. Country = categorical variable (1 = UK, 2 = Australia). Ratings scales: arousal = 1 (calm) to 9 (activated); familiarity, complexity, and pattern = 1 (very unfamiliar/simple/random) to 7 (very familiar/complex/patterned). Valence was controlled for along with group membership in Step 1.

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Table 5. Hierarchical linear regression statistics and significance values for predictor variables (acoustic and aesthetic properties) with fascination score as dependent variable.

	IV	*t*	*B*	*SE B*	*β*
Step 2	Sound level	-1.35 ^{ns}	-.03	.03	-.18
$R^2_{Adj}Chg$ = .23	Harmonics	2.59*	.04	.01	.37
FChg (4, 41) = 4.49**	Frequency	1.96 ^{ns}	< .001	< .001	.28
	Country	-.50 ^{ns}	-.09	.18	-.06
Step 3a	Sound level	-1.29 ^{ns}	-.03	.03	-.18
$R^2_{Adj}Chg$ < .001	Harmonics	2.56*	.04	.01	.37
FChg (1, 40) = .01 ^{ns}	Frequency	1.81 ^{ns}	< .001	< .001	.27
	Country	-.32 ^{ns}	-.07	.23	-.05
	Familiarity	.10 ^{ns}	.01	.09	.02
Step 3b	Sound level	-2.85**	-.04	.02	-.23
$R^2_{Adj}Chg$ = .47	Harmonics	4.14***	.04	.01	.36
FChg (1, 40) = 72.23***	Frequency	.41 ^{ns}	< .001	< .001	.04
	Country	-.89 ^{ns}	-.10	.11	-.07
	Complexity	8.50***	.59	.07	.70
Step 3c	Sound level	-2.06*	-.05	.03	-.29
$R^2_{Adj}Chg$ = .05	Harmonics	3.18**	.05	.01	.45
FChg (1, 40) = 4.67*	Frequency	1.72 ^{ns}	< .001	< .001	.23
	Country	-.96 ^{ns}	-.17	.18	-.12
	Pattern	-2.16*	-.27	.13	-.29
Step 3d	Sound level	-1.85 ^{ns}	-.03	.02	-.16
$R^2_{Adj}Chg$ = .51	Harmonics	3.52***	.03	.01	.31
FChg (3, 38) = 28.93***	Frequency	-.19 ^{ns}	< .001	< .001	-.02
	Country	.54 ^{ns}	.07	.13	.05
	Familiarity	1.42 ^{ns}	.08	.05	.14
	Complexity	8.54***	.70	.08	.84
	Pattern	1.92 ^{ns}	.18	.10	.19

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N = 50. *** $p \leq .001$, ** $p \leq .01$, * $p \leq .05$, ^{ns} Not significant. Country = categorical variable (1 = UK, 2 = Australia). Ratings scales: fascination = 0 (not at all) to 6 (completely); familiarity, complexity, and pattern = 1 (very unfamiliar/simple/random) to 7 (very familiar/complex/patterned).

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Table 6. Hierarchical linear regression statistics and significance values for predictor variables (acoustic and aesthetic properties) with being away score as dependent variable.

	IV	*t*	*B*	*SE B*	*β*
Step 2	Sound level	-2.12*	-.06	.03	-.26
$R^2_{Adj}Chg$ = .40	Harmonics	3.36**	.05	.02	.43
FChg (4, 41) = 8.69***	Frequency	2.74**	< .001	< .001	.34
	Country	-1.18 ns	-.23	.20	-.13
Step 3a	Sound level	-1.84 ns	-.05	.03	-.22
$R^2_{Adj}Chg$ = .03	Harmonics	3.55***	.05	.02	.44
FChg (1, 40) = 3.04 ns	Frequency	2.16*	< .001	< .001	.28
	Country	.11 ns	.03	.25	.02
	Familiarity	1.74 ns	17	.10	.26
Step 3b	Sound level	-2.85**	-.07	.02	-.29
$R^2_{Adj}Chg$ = .18	Harmonics	3.96***	.05	.01	.42
FChg (1, 40) = 18.89***	Frequency	1.76 ns	< .001	< .001	.19
	Country	-1.46 ns	-.24	.17	-.14
	Complexity	4.35***	.46	.11	.44
Step 3c	Sound level	-2.14*	-.06	.03	-.28
$R^2_{Adj}Chg$ < .001	Harmonics	3.34**	.06	.02	.44
FChg (1, 40) = .24 ns	Frequency	2.62**	< .001	< .001	.33
	Country	-1.25 ns	-.26	.20	-.14
	Pattern	-.49 ns	-.07	.15	-.06
Step 3d	Sound level	-1.71 ns	-.04	.02	-.16
$R^2_{Adj}Chg$ = .30	Harmonics	3.67***	.04	.01	.35
FChg (3, 38) = 14.34***	Frequency	.80 ns	< .001	< .001	.08
	Country	1.01 ns	.18	.18	.10
	Familiarity	2.94**	.21	.07	.33
	Complexity	5.99***	.70	.11	.65
	Pattern	2.52*	.33	.13	.28

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N = 50. *** $p \leq .001$, ** $p \leq .01$, * $p \leq .05$, ^{ns} Not significant. Country = categorical variable (1 = UK, 2 = Australia). Ratings scales: being away = 0 (not at all) to 6 (completely); familiarity, complexity, and pattern = 1 (very unfamiliar/simple/random) to 7 (very familiar/complex/patterned).

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Highlights

- Associations with bird sounds were thematically analysed.
- Restorative bird sounds had positive, nature-based associations.
- Non-restorative bird sounds had negative, exotic, and non-avian associations.
- Findings show relationships between semantic values and restorative perceptions.

Abstract

Bird sounds are related to perceptions of attention restoration and stress recovery, but the role of associations in such perceptions is understudied. 174 adult residents of the United Kingdom rated 50 bird sounds on perceived restorative potential (PRP) and provided qualitative data on associations with each sound. Bird sounds were associated with imagined environments, birds and other animals, time and season, and activities within the environment. Bird sounds rated as high in PRP were associated with green spaces, spring and summer, daytime, and active behaviours in the environment. Low-PRP bird sounds were associated with exotic and marine environments, non-avian animals, and showed a non-significant trend towards associations with negative bird behaviour. These findings highlight connections between semantic values and restorative perceptions of natural stimuli. Such connections can inform top-down approaches to study of

restorative environments and may benefit conservationists seeking to improve bonds between people and wildlife.

Introduction

In recent years, study of restorative environments has broadened to include not just visual experience but also that of environmental sounds. Reflecting similar findings in the visual domain, natural sounds such as wind, water, and birds are perceived to be pleasant, relaxing, and potentially restorative (e.g. Björk et al., 2008, Grahn and Stigsdotter, 2010, Payne, 2013), and can lead to greater recovery from stress than sounds from the built environment (Alvarsson et al., 2010, Benfield et al., 2014, Medvedev et al., 2015). Across these findings, birds recur as a characteristic sound of nature; one that individuals bond with and draw inspiration and symbolism from (Mynott, 2009, N'gweno, 2010, Ratcliffe et al., 2013).

Despite the increased interest in restorative natural sounds, one topic that remains under-examined in both the visual and auditory domains is *why* certain environments and environmental stimuli can be perceived as restorative. In particular, the role of meanings, associations, and other semantic qualities of natural environments and stimuli cries out for further study, as noted by Pretty (2004) and Pretty et al. (2015). In his presentation of an affective, psycho-evolutionary framework of restorative environments, Ulrich (1983, p. 92) notes that, "Evaluation may be accompanied by memories and associations …" yet relationships between restorative perceptions or outcomes and these top-down appraisals remain speculative, due to lack of systematic study. Furthermore, Shaw, Coyle, Gatersleben, and Ungar (2015) report on individuals' imagined restorative environments built up from non-visual perceptions. These aspects of the literature indicate that both past and imagined future experiences can influence perceptions of restorative potential and restoration.

Despite being but one part of the natural world, birds are regarded as one of the most important types of animals and sounds that individuals experience in nature (Cox and Gaston, 2015, Curtin, 2009, Ratcliffe et al., 2013), and they are particularly rich in semantic values and associations (Mynott, 2009). Beyond merely conveying purely practical information, bird sounds can have symbolic value that may affect how they are cognitively and affectively appraised, and perhaps how restorative they are perceived to be. Throughout time birds have symbolised concepts, events, and aspects of human nature as told through stories and folklore, to the extent that they feature more than any other animal in Aboriginal Australian stories (Tidemann & Whiteside, 2010). N'gweno (2010) notes that bird sounds are often used to convey meaning and messages in folklore, such as the changing seasons, life events, and fortunes. She suggests that sound is particularly relevant in bird identification and knowledge because they are often heard before they are seen, thus making the bird's sound a symbol in itself for the bird and the concepts it represents. For this reason, bird sounds are an excellent vehicle through which to examine meanings associated with natural stimuli, and in particular how those meanings relate to perceptions of restoration in order to address the semantic gap in the field, described above.

While birdsong in a holistic sense is generally considered to be pleasant (Björk et al., 2008, Grahn and Stigsdotter, 2010), differences occur between bird species in terms of how pleasant or relaxing they are perceived to be (Björk, 1985, Cox and Gaston, 2015, Ratcliffe et al., 2013). Ratcliffe et al.

(2013) showed that the associative values of different bird sounds are particularly important in establishing affective appraisals and restorative perceptions. For example, one participant in Ratcliffe et al. (2013, p. 224) described “screeches, owls hooting” as “archetypal spooky sounds … Because they’re frightening”, suggesting that certain bird sounds can act as symbols for negative valence or fear in an abstract sense, and in turn these sounds are not considered restorative. This view is supported by Cox and Gaston (2015), who suggest that songbirds are preferred over calling, non-songbirds because they are less likely to be associated with aggressive or otherwise threatening behaviour.

The presence of threat in nature has been shown to reduce restorative potential and outcomes in these environments; for example, Andrews and Gatersleben (2010) and Gatersleben and Andrews (2013) reported that environments low in both prospect and refuge (signifiers of safety and security) were associated with reduced restorative perceptions and outcomes. Herzog and Rector (2009) noted that a vignette indicating the presence of a threatening stranger reduced restorative perceptions of an imagined natural environment, and Bixler and Floyd (1997) indicated that non-human threats, such as wild animals or risk of getting lost, may also be found in natural environments. These findings correspond with prevailing theories of restorative environments, in that the presence of threat is likely to increase arousal and negative affective appraisals, limiting restoration from stress (Ulrich, 1983), and to impose cognitive demands that limit restoration from directed attention fatigue (Kaplan and Kaplan, 1989, Kaplan, 1995). However, there is a lack of existing research on how the spontaneous associations with the presence or absence of threat linked to birds might relate to restorative potential, and particularly the potential of specific stimuli such as bird sounds.

Bird sounds can be symbols for times of year associated with resources. Sometimes these associations are generated through folklore or cultural knowledge, and at other times they are formed on the basis of personal memories. For example, in Ratcliffe et al. (2013, p. 65) one participant said of the wood pigeon’s song, “That kind of reminds me of summer and sort of long, hot summers”, and Mynott (2009) notes that the sound of the crane is associated with autumn and bringing in the harvest. Tidemann and Whiteside (2010) describe an Aboriginal Australian story in which the sound of the Channel-billed Cuckoo is associated with both the start of the rainy season and the presence of manna sugar, an energy-rich food source. In hearing bird sounds, listeners may be made aware of the presence of life-giving elements of nature. It is possible that these sounds may have restorative potential through their associations with vitality and biodiversity, perhaps linking to concepts of survival (Ulrich, 1983).

Birds and their sounds can also be symbolic of positively and negatively valenced concepts. In Australian Aboriginal storytelling, the Laughing Kookaburra’s sound serves as a symbol of both merriment (Tidemann & Whiteside, 2010) and new beginnings, such as daybreak. Mynott (2009) indicates that symbolic associations with birds differ with culture and can be concurrent; for example, the owl has been associated with both wisdom and death, and the robin with both life in the depths of winter and concepts of death and sacrifice. Bird sounds, then, can be associated with concepts and events greater than themselves, and can generate affective appraisals based on those symbolic associations. However, it is not known to what extent this might relate to their restorative potential. Also underexplored are potential associations between nature, including bird sounds, and

personal symbolism in the form of memories of one's past, and how these too might relate to restorative perceptions as hypothesised by Ulrich (1983).

If bird sounds can symbolise ideas such as summer, food, death, and beginnings, perhaps they can also symbolise the wider environment that they are drawn from, as shown in Shaw et al. (2015) where participants imagined detailed environments based on the sounds that they heard around them. Tidemann and Whiteside (2010) note that, alongside other animals, birds are invoked in folklore and mythology to explain the formation of topographical features and constellations of stars. In Ratcliffe et al. (2013, p. 225), bird sounds were sometimes discussed in the context of being in green spaces such as a garden, and of doing activities in those spaces. For example, one participant said, "We sit and feed and look after the birds a lot, so certainly I would sit and listen to the birds …", suggesting that the bird sounds he described were linked to the act of both sitting outdoors and caring for the birds, linking themes of environments and activities within them. These findings suggest that bird sounds may trigger associations with natural environments and activities in nature, experiences of which are known to be restorative in themselves (e.g. Hartig, Evans, Jamner, Davis, & Gärling, 2003), but it is not clear how these associations might vary depending on the type of bird sound.

This study explored the types of associations and memories generated by listening to 50 bird sounds previously quantitatively rated on perceived restorative potential (PRP). In particular, the study aimed to understand whether a range of bird sounds rated as high, moderate, or low on PRP would generate different associative themes. This mixed-methods approach was undertaken since, as noted above, a single bird sound can be associated with a range of meanings from the practical or instrumental to the highly symbolic or personal, making qualitative techniques most appropriate for identifying these different meanings, which can themselves then by subjected to quantitative analyses. PRP relates to a single meaning (suitability for restoration), making it more appropriate for quantitative measurement. By combining the two techniques, this study aimed to examine associations with bird sounds in participants' own words whilst relating these back to measurable differences in perceived restorative value.

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Section snippets

Participants and design

174 adults aged between 18 and 68 (M=35.52 years, SD=13.22), who self-reported ordinarily being residents of the United Kingdom, were recruited from the general population through online and local advertising in London and the South East of England. This took the form of recruitment via social media, academic electronic mailing lists, snowball sampling via email, and posters placed on

community and university notice boards. 123 were female, 50 were male, and one did not indicate gender. …

Analyses

Average PRP scores were calculated per bird sound across participants, and these are shown in Table 1. These scores were calculated based on responses from the overall sample of 174 participants, in order to increase reliability.

Qualitative data were analysed through a version of thematic analysis (Braun and Clarke, 2006, Hsieh and Shannon, 2005, Ratcliffe et al., 2013), enabling identification of key themes. Responses from the 116 participants who provided data on associations and memories …

Associations with bird sounds and relationships with PRP

Thematic content analysis of associations with bird sounds revealed four master themes: environment, animals, time and season, and activities in the environment. High-PRP bird sounds tended to generate associations with green, verdant environments and with concepts of home and one's garden, while low- or moderate-PRP bird sounds were associated with exotic and marine environments or built spaces. High- and low-PRP sounds were also generally dissociated on the basis of their connections to …

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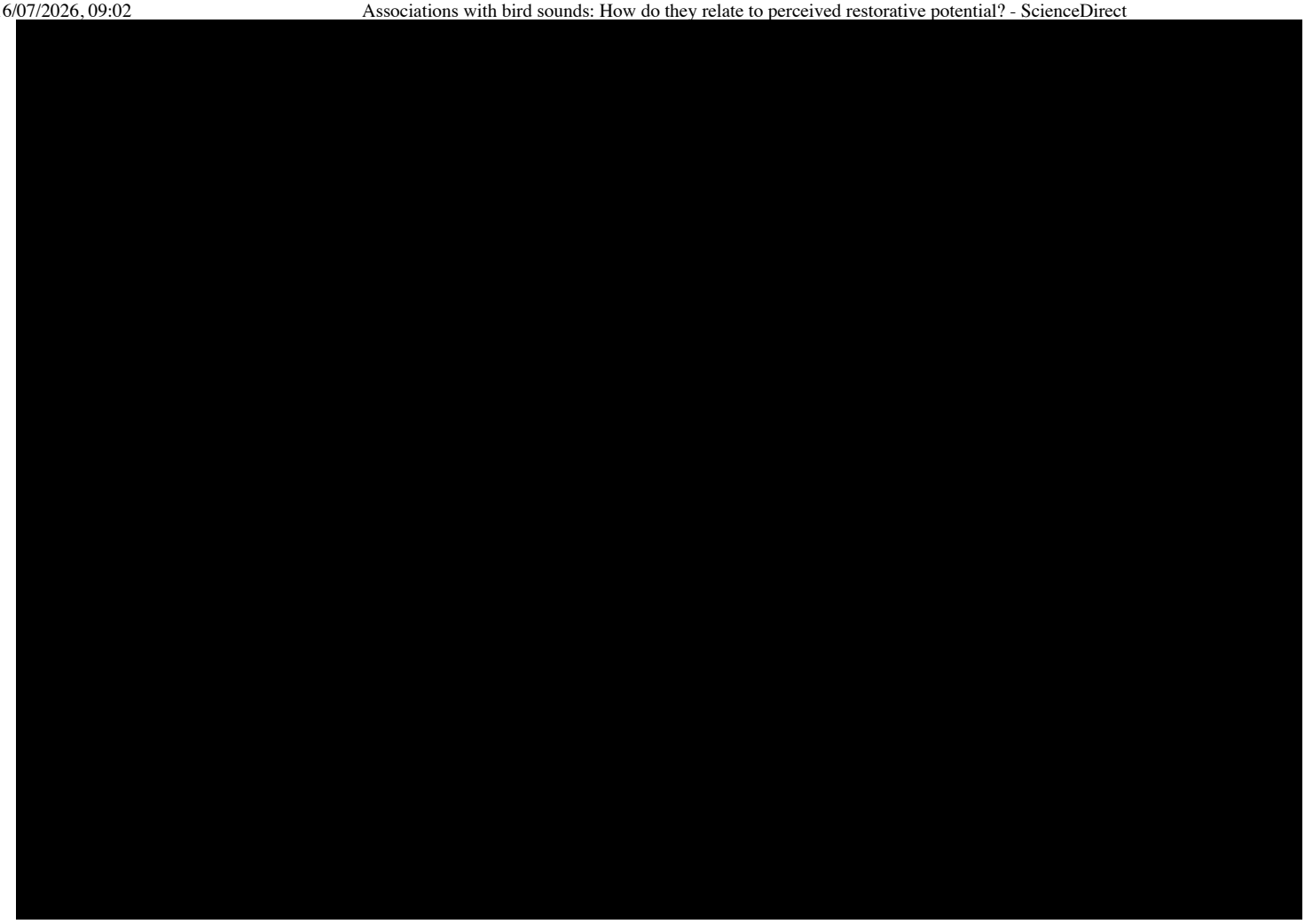
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BRIEF REPORT

Of cricket chirps and car horns: The effect of nature sounds on cognitive performance

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Abstract
Attention restoration theory (ART) posits that stimuli found in nature may restore directed attention functioning by reducing demands on the endogenous attention system. In the present experiment, we assessed whether nature-related cognitive benefits extended to auditory presentations of nature, a topic that has been understudied. To assess directed attention, we created a composite measure consisting of a backward digit span task and a dual n-back task. Participants completed these cognitive measures and an affective questionnaire before and after listening to and aesthetically judging either natural or urban soundscapes (between-participants). Relative to participants who were exposed to urban soundscapes, we observed significant improvements in cognitive performance for individuals exposed to nature. Urban soundscapes did not systematically affect performance either adversely or beneficially. Natural sounds did not differentially change positive or negative affect, despite these sounds being aesthetically preferred to urban sounds. These results provide initial evidence that brief experiences with natural sounds can improve directed attention functioning in a single experimental session.

Keywords Attention · Cognitive and attentional control · Attention restoration theory · Nature

Introduction

The psychological benefits of interacting with nature have been discussed for well over a century (e.g., Olmsted, 1993), with research over the past few decades assessing how interactions with nature specifically may benefit cognition and cognitive development (e.g., Bratman, Hamilton, & Daily, 2012). For example, the extent of available green space has been positively associated with the development of executive functions in children, even after controlling for factors such as socioeconomic status (Dadvand et al., 2015). Even brief interventions in which participants take a walk through nature or view nature images on a computer screen have been shown to improve the functioning of directed attention relative to interventions in which participants are exposed to more urban environments (Berman, Jonides, & Kaplan, 2008).

One prominent account of how nature may improve aspects of cognition is *attention restoration theory* (ART), which posits that nature environments are particularly well-suited for reducing demands on the endogenous attention system, thereby allowing subsequent restoration of attentional functioning (e.g., Kaplan, 1995). The fact that simply viewing pictures of nature environments can improve performance on tasks requiring directed attention (Berman et al., 2008) suggests that nature, in part, may improve performance through the visual features that differentiate natural and urban scenes (see Berman et al., 2014), which may engage attentional mechanisms in a manner that restores directed attention. However, the focus on visual depictions of nature in the ART literature has resulted in a relative paucity of research on other modalities, such as audition. As such, the present experiment tests whether auditory representations of nature confer similar benefits to directed-attention functioning.

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Beyond ART, two broad research findings support potential cognitive benefits from experiencing nature sounds. First, prior studies have demonstrated widespread associations between noise levels and health. Noise pollution (e.g., urban environmental noises with sustained, high-amplitudes) has been associated with greater amounts of reported stress and distraction (e.g., de Paiva Vianna, Cardoso, & Rodrigues, 2015), which can lead to chronic learning and attention problems (see Hammer, Swinburn, & Neitzel, 2014). Thus, natural sounds may improve aspects of cognition relative to urban sounds because these two classes of sounds generally differ with respect to their amplitude in the real world (see McDonald et al., 1995), with nature sounds being thought to provide a quiet respite from urban environments (Mace, Bell, & Loomis, 2004). In this kind of framework, however, nature sounds may not confer any cognitive benefits relative to urban sounds when presented at the same amplitude.

A second reason why natural sounds may improve cognitive functioning is captured by *stress reduction theory* (SRT; Ulrich, 1983). SRT asserts that the aesthetic and affective value of experiences with nature can lower stress levels, which may in turn benefit cognitive performance. In support of SRT, natural sounds have been shown to reduce physiological symptoms of stress and improve affect (e.g., Alvarsson, Wiens, & Nilsson, 2010; Benfield, Taff, Newman, & Smyth, 2014; Ulrich et al., 1991), and, moreover, certain classes of natural sounds (birdsong) are *perceived* to both lower stress and restore attention (e.g., Ratcliffe, Gatersleben, & Sowden, 2013). Thus, nature-related benefits to cognitive functioning are compatible with both ART and SRT, though under SRT one would expect cognitive benefits to be a consequence of affective changes.

However, prior research has not found convincing evidence for the benefits of natural sounds on the functioning of directed attention. Emfield and Neider (2014) assessed how nature interventions improved performance on directed attention tasks. The authors found an improvement from pre- to post-intervention (i.e., a practice effect), but no nature-related performance advantage relative to urban stimuli. However, the underlying research question was not about natural sounds specifically, and as such natural (vs. urban) sounds were not considered independently in any analysis. More recently, Abbott, Taff, Newman, Benfield, and Mowen (2016) assessed how natural sounds influenced backward digit span (BDS) performance, ultimately finding no difference between natural and urban sound conditions. However, in this design, all participants viewed a video of Yosemite National Park concurrent with the sounds, and "urban" sounds actually consisted of natural sounds (birdsong) that were periodically interrupted by manmade sound objects, making it difficult to draw strong conclusions about the effects of natural and urban sounds on cognitive performance.

Aims and hypotheses

The present experiment provides a more direct test of whether randomly assigning participants to hear nature versus urban soundscapes improves the functioning of directed attention. In line with previous work from the visual domain (e.g., Berman et al., 2008; Berto, 2005; Bourrier, Berman, & Enns, 2018), the primary hypothesis was that brief experiences with nature sounds, relative to urban sounds, will result in performance improvements on cognitive tasks requiring directed attention.

To address whether any nature-related cognitive improvements could be explained by affective changes, which would be predicted under SRT, participants provided aesthetic ratings of the sounds they heard as well as rated their positive and negative affect before and after the sound intervention. Aesthetic judgments have been interpreted as an affective response in the context of SRT (Ulrich, 1983), and previous investigations of nature-related cognitive benefits in vision have examined how aesthetic ratings of experienced nature relate to cognitive improvements (Berman et al., 2008).

Given that prior research has established that nature stimuli are aesthetically preferred to urban stimuli (e.g., Kaplan, Kaplan, & Wendt, 1972; Kardan et al., 2015) and that experiences with nature can improve positive affect and reduce negative affect (e.g., Benfield et al., 2014; Bratman, Daily, Levy, & Gross, 2015), we hypothesized that, relative to urban sounds, nature sounds will: (1) be aesthetically preferred, (2) increase positive affect, and (3) decrease negative affect. Importantly, however, under SRT these aesthetic and affective changes should significantly relate to any observed cognitive improvements. Thus, there are two overarching aims of this work. The first aim is to assess whether nature sounds can improve aspects of cognitive performance. The second aim is to ground any observed nature-related cognitive benefits in the context of either ART or SRT.

Method

Participants and design

Sixty-five individuals participated in the experiment. Two were excluded due to task non-compliance (i.e., failing to perform one of the tasks as indicated by the instructions), leaving 63 analyzable participants (M = 20.9 years, SD = 3.87 years, range = 18–44 years, 35 female, 25 male, three non-binary/prefer not to answer). Participants were recruited from the University of Chicago campus and surrounding community via the use of an online system (Sona Systems), in which participants read a short description of the experiment and then signed up for one of several pre-specified time slots posted by the experimenter. The experiment was advertised in this online system as a study on perception and memory (i.e., there was no

explicit mention of nature or urban stimuli); all participants were debriefed and informed of the experiment's hypotheses after participation. There were 31 participants who heard natural sounds and 32 participants who heard urban sounds. All participants provided informed consent and were treated in accordance with the NIH guidelines for interacting with human participants. Participants were compensated with either $10 or 1 h of course credit for experimental participation.

The experiment adopted a 2 (time: pre-intervention, post-intervention) x 2 (soundscape: natural, urban) mixed factorial design, with time as the within-participant factor and soundscape as the randomly-assigned, between-participant factor.

Materials

The 40 natural and 40 urban soundscapes, which are available on the Open Science Framework (https://osf.io/kjuzr/), were originally selected from an online video-sharing website for another research project currently in progress (Van Hedger et al., 2018). The number of total soundscapes was influenced by conceptually similar work in the visual domain (e.g., Berman et al., 2008 used 50 natural and 50 urban images). The natural soundscapes primarily contained sounds of birdsong, moving water (e.g., rainfall, ocean waves), insects (e.g., crickets), and wind. The urban soundscapes primarily contained sounds of traffic, café ambiance (with unintelligible speech), and machinery (e.g., the "hum" of an air conditioner). Moreover, each soundscape was not necessarily limited to a single sound-producing object (e.g., a single nature soundscape could contain ocean waves and birdcalls). Each soundscape was 20 s in duration with a 500-ms linear fade in and fade out. Additionally, we normalized the average loudness of the soundscapes by matching root-mean-square (RMS) amplitude and presented the files at a comfortable listening level of approximately 70 dB SPL (e.g., Dobie & Van Hemel, 2004). To verify that the selected soundscapes represented natural and urban categories, a separate group of participants (n = 50) rated 5-s versions of each soundscape on a 7-point scale (where 1 corresponded to "very urban" and 7 corresponded to "very natural"). In this prior testing, ratings for the natural and urban soundscapes were completely non-overlapping (i.e., the lowest-rated natural soundscape was rated higher than the highest-rated urban soundscape). The data from this prior study are available on Open Science Framework [redacted]

Measures

All measures used in the experiment are available on the Open Science Framework (https://osf.io/r8yv6/).

Affective The Positive and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988) required participants to rate the extent to which they had felt 10 positive and 10 negative adjectives over the past few hours. Participants made their ratings on a 5-point scale and the 20 terms were presented in a random order. The internal consistency of the positive affect (PA) and negative affect (NA) subscales, assessed through Cronbach's alpha, was high for both administrations (NA pre-intervention: α = .86; NA post-intervention: α = .90; PA pre-intervention: α = .88; PA post-intervention: α = .91). The PANAS was presented with E-Prime 2.0 (Psychology Software Tools: Sharpsburg, PA, USA).

The aesthetic ratings were collected during the presentation of the soundscapes. After each sound, participants provided an aesthetic rating, operationalized as a "like-dislike" affective response (e.g., see Zajonc, 1980), on a 3-point scale (with 1 corresponding to "dislike," 2 corresponding to "neutral," and 3 corresponding to "like"). Responses were averaged across the 40 sounds to create a mean aesthetic variable for each participant.

Cognitive Directed attention was operationalized through the construction of a composite cognitive measure, consisting of both the dual n-back (DNB) task and the BDS task. The BDS has been a common assessment of directed attention within the ART literature (e.g., Berman, Jonides, & Kaplan, 2008; Emfield & Neider, 2014); thus, the selection of BDS was largely motivated by these prior reports. DNB has not been previously administered in the context of ART, yet it was selected because it also places demands on directed attention (see Lilienthal, Tamez, Shelton, Myerson, & Hale, 2013) and shares variance with BDS (see Redick & Lindsey, 2013) – ostensibly because both tasks place demands on directed attention. As such, a composite measure of BDS and DNB should better reflect directed attention functioning by reducing task-specific variance. It should also be noted that the use of a composite measure is in line with prior ART experiments (e.g., Cimprich & Ronis, 2003; Tennessen & Cimprich, 1995).

The BDS consisted of 14 trials, similar to Berman et al. (2008, 2012) and Emfield and Neider (2014). The task was non-adaptive, in that the digit span was not increased or decreased based on participant performance. Participants completed two trials for each digit span length (beginning with three and ending with nine). On each trial, each digit was separately presented for 1,000 ms, presented in either the auditory or the visual modality (counterbalanced across participants). Participants typed their response in a designated text box and were not time limited. Performance was operationalized as the total number of correct trials out of 14. The BDS was presented with E-Prime 2.0.

The DNB consisted of both a 2-back block of trials and 3-back block of trials. On each trial, a spoken letter and blue square were simultaneously presented. The square could appear in eight locations around a center fixation cross, and there were eight possible letters. Participants pressed designated keys ("A" or "L") if the spoken letter or current location of the square matched the letter or square location n trials previously (i.e., either 2- or 3-back). If both

the letter and the square matched, participants pressed both keys. No keys had to be pressed for non-matching trials. There were practice runs of 10 trials (excluding the first *n* presentations) for both the 2-back and 3-back levels, during which participants received feedback but data was not recorded. Each level (2- and 3-back) was divided into two separate blocks of 20 trials (excluding the first *n* trials). Participants always completed the 2-back blocks before the 3-back blocks. There was a fixed ratio of trial types (50%: no match, 20%: auditory match, 20%: visual match, 10%: both auditory and visual match), which were pseudo-randomly presented during each run. For each participant, we calculated a single d' score (e.g., Macmillan & Creelman, 2005), aggregated across the 2- and 3-back. The DNB was accessed through the Millisecond Test Library and was presented with Inquisit 4.0 (Millisecond Software: Seattle, WA, USA).

Procedure

After providing written consent, participants completed the PANAS, BDS, and DNB in this order. These pre-intervention assessments took approximately 20 minutes to complete. Participants then heard 40 natural or urban soundscapes, depending on the condition to which they were randomly assigned. This portion of the experiment took approximately 15 min to complete. Following the natural or urban sound exposure, participant retook the PANAS, BDS, and DNB in this order. Finally, participants filled out a brief questionnaire, which collected basic demographic information as well as required participants to write down their thoughts as to the purpose of the study, as well as whether they had participated in any similar study.

A subset of participants (17 of 63) correctly identified the general purpose of the study, in that they guessed that the soundscapes might influence their attention or memory (Natural Condition: 10, Urban Condition: 7). As such, all analyses reported in the paper are performed with all 63 participants ("Full") as well as just the 46 participants who were naïve to the purpose of the experiment ("Naïve").

Calculation of composite cognitive measure

To create a composite measure from the BDS and DNB tasks, we converted participants' scores for each task (number of correct trials for BDS and d' for DNB) to *z* scores; i.e., (raw score – mean) / standard deviation. Each participant's BDS and DNB *z* score was then averaged together, separated by time (pre- and post-intervention). Further details on how the composite measure was calculated can be accessed on the Open Science Framework [redacted].

Statistical analyses and power

All analyses were calculated using JASP 0.8.2 (JASP Team, 2018). We report Bayes factors (BF) in the assessment of evidence for or against a given hypothesis. The BF is a ratio that contrasts the likelihood of the data arising from the null hypothesis compared to the alternative hypothesis (e.g., see Jarosz & Wiley, 2014). As such, one advantage of a BF over a *p*-value is that it quantifies the relative evidence in favor of either the null or the alternative hypothesis. In the context of ANOVA models, the BF represents the evidence for including a given effect, which is calculated by comparing all models with this effect to all models without this effect. In the context of *t*-tests, the BF represents the evidence for the alternative versus the null hypothesis. As recommended by Wagenmakers et al. (2017), the default priors in JASP were used, which imply equal probabilities for the null and alternative hypotheses. Finally, for purposes of interpretability, each analysis also reports test statistics and *p*-values from traditional null hypothesis significance testing.

We additionally calculated *a priori* power in G*Power (Faul, Erdfelder, Buchner, & Lang, 2009) based on the experimental design and assumptions of small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$) effect sizes (Cohen, 1988). In these analyses, to achieve a statistical power of 0.8, the present experiment would need a sample size of 620 to detect a small effect, a sample size of 102 to detect a medium effect, and a sample size of 42 to detect a large effect. The effect size at which the present sample size would reach 0.8 power corresponds to $d = 0.63$, which is between a medium and a large effect.

Results

All reported analyses and associated data files can be accessed on the Open Science Framework [redacted] The analyses are based on summary statistics; however, the raw (trial-by-trial) data for each task are also available on the Open Science Framework ([redacted]).

Affective measures

Aesthetic ratings

Natural soundscapes were aesthetically preferred over urban soundscapes (Full: t (61) = 5.61, $p < .001$, $d = 1.41$, BF = 2.41e4; Naïve: t (44) = 4.65, $p < .001$, $d = 1.38$, BF = 610.2). For all 63 participants, the mean rating of natural soundscapes was 2.31 (SD = 0.37) and the mean rating of urban soundscapes was 1.84 (SD = 0.28). For the subset of 46 naïve participants, the mean rating of natural soundscapes was 2.23 (SD = 0.41) and the mean rating of urban soundscapes was 1.82 (SD = 0.29).

PANAS

We analyzed changes in the PANAS using a 2 (time: pre-, post-) × 2 (soundscape: nature, urban) mixed factorial ANOVA and Bayesian equivalent. For positive affect (PA), there was a

significant main effect of time (Full: F (1, 61) = 10.62, p = .002, d = 0.41, BF = 17.12; Naïve: F (1, 44) = 9.26, p = .004, d = 0.45, BF = 9.327), characterized by overall lower scores post-intervention compared to pre-intervention. There was a marginal main effect of soundscape type when considering all participants – with natural soundscape participants exhibiting lower scores than urban soundscape participants – though this effect was not significant when limited to the naïve participants (Full: F (1, 61) = 3.28, p = .075, d = 0.46, BF = 1.22; Naïve: F (1, 44) = 2.32, p = .135, d = 0.45, BF = 0.93). The interaction between time and soundscape type was not significant (Full: F (1, 61) = 0.22, p = .644, d = 0.12, BF = 0.27; Naïve: F (1, 44) = 0.13, p = .718, d = 0.11, BF = 0.29).

For negative affect (NA), there was also a main effect of time (Full: F (1, 61) = 9.73, p = .003, d = 0.39, BF = 9.87; Naïve: F (1, 44) = 9.74, p = .003, d = 0.44, BF = 8.36), characterized by overall lower scores post-intervention compared to pre-intervention. However, the main effect of soundscape type (Full: F (1, 61) = 0.39, p = .536, d = 0.16, BF = 0.52; Naïve: F (1, 44) = 0.77, p = .386, d = 0.26, BF = 0.61), in addition to the interaction between time and soundscape type (Full: F (1, 61) = 2.50, p = .119, d = 0.40, BF = 0.71; Naïve: F (1, 44) = 1.45, p = .235, d = 0.36, BF = 0.50), was not significant for either the full or the naïve group of participants.

Cognitive measure

We analyzed changes in the composite cognitive measure using a 2 (time: pre-, post-) × 2 (soundscape: nature, urban) mixed factorial ANOVA and Bayesian equivalent. In this analysis, the main effect of time was significant (Full: F (1, 61) = 12.91, p < .001, d = 0.42, BF = 20.857; Naïve: F (1, 44) = 8.42, p = .006, d = 0.37, BF = 3.13), with participants displaying higher post-intervention compared to pre-intervention scores, i.e., a learning effect. The main effect of soundscape type was not significant, and the Bayes factor was inconclusive (Full: F (1, 61) = 3.08, p = .084, d = 0.44, BF = 1.127; Naïve: F (1, 44) = 1.94, p = .171, d = 0.41, BF = 0.89). Critically, there was a significant interaction between time and soundscape type (Full: F (1, 61) = 7.92, p = .007, d = 0.71, BF = 6.651; Naïve: F (1, 44) = 6.58, p = .014, d = 0.76, BF = 3.08), plotted in Fig. 1. This interaction was characterized by a greater improvement in the natural sound condition compared to the urban sound condition, and the effect size of the interaction can be interpreted as medium to large (Cohen, 1988).

Follow-up analyses demonstrated that the interaction between time and soundscape was best conceptualized as a nature-related benefit to performance. Performance on the cognitive measure did not significantly differ between participants in the natural and urban soundscape conditions during pre-intervention (Full: t (61) = 0.74, p = .462, d = 0.19, BF = 0.324; Naïve: t (44) = .61, p = .545, d = 0.18, BF = 0.341); by post-intervention, however, participants assigned to natural soundscapes were significantly outperforming participants assigned to urban soundscapes (Full: t (61) = 2.59, p = .006, d = 0.65, BF = 8.054; Naïve: t (44) = 2.13, p = .020, d = 0.63, BF = 3.395). Within participants, the cognitive improvement from pre- to post-intervention was significant and positive for natural sounds (Full: t (30) = 4.56, p < .001, d = 0.82, BF = 311.1; Naïve: t (20) = 4.64, p < .001, d = 1.01, BF = 182.3) and not significant for urban sounds (Full: t (31) = 0.55, p = .587, d = 0.10, BF = 0.217; Naïve: t (24) = 0.26, p = .796, d = 0.05, BF = 0.22).

Relationship between affective and cognitive measures

For our affective measures, we did not find evidence that listening to natural versus urban soundscapes differentially influenced participants' positive or negative affect, measured by the PANAS, even though natural sounds were more preferred aesthetically to urban sounds. However, these analyses by themselves do not answer whether the affective measures relate to the observed improvement in cognitive performance. To assess this question, we correlated cognitive improvement (post- minus pre-intervention score) with changes in the PANAS (both positive and negative affect), as well as with aesthetic ratings.

The relationship between changes in positive affect and cognitive improvement was not significant (Full: r (61) = .14, p = .276, d = 0.28, BF = 0.28; Naïve: r (44) = .06, p = .703, d = 0.12, BF = 0.20). The relationship between changes in negative affect and cognitive improvement was also not significant (Full: r (61) = .15, p = .231, d = 0.30, BF = 0.32; Naïve: r (44) = .11, p = .455, d = 0.22, BF = 0.24). Finally, the relationship between aesthetic ratings and cognitive improvement was also not significant (Full: r (61) = .18, p = .168, d = 0.37, BF = 0.40; Naïve: r (44) = .22, p = .147, d = 0.45 BF = 0.51).

For completeness, the means, standard deviations, and effect sizes of changes from pre- to post-intervention for each of the measures (separated by full and naïve participant groups) are provided in Table 1.

Discussion

The present results demonstrate that brief experiences with natural sounds can produce benefits to performance on cognitively demanding tasks. This nature-related cognitive improvement – which represents a medium-to-large effect size – cannot be attributed to differences in mean amplitude between natural and urban sounds – which is a critical factor in real-world health outcomes of living in urban versus natural spaces (Hammer et al., 2014) – given that both classes of sounds were normalized to the same amplitude and presented at a comfortable listening volume to participants. The observed cognitive benefits also were not significantly related to any of our affective measures, suggesting that cognitive benefits from nature are not necessarily driven by affective responses to nature.

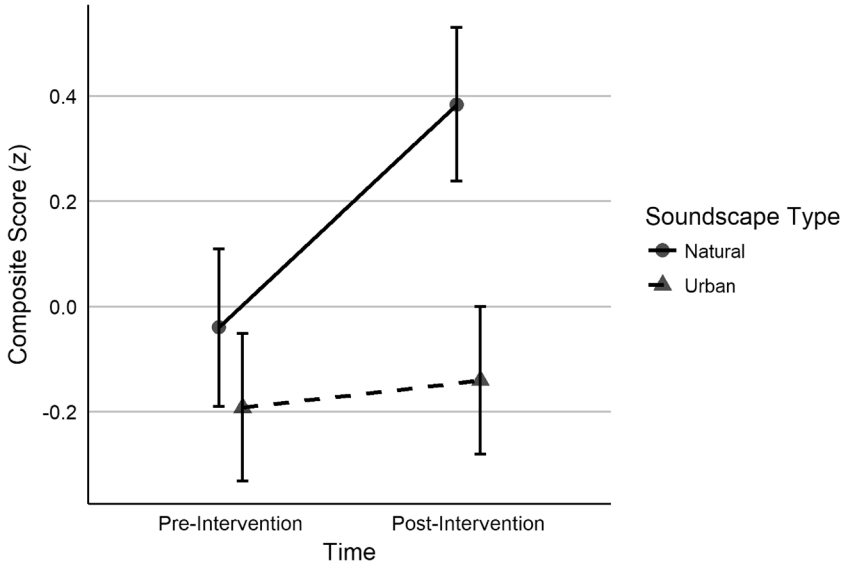


Fig. 1 Composite cognitive measure, plotted as a function of time (pre-intervention, post-intervention) and soundscape type (natural, urban). Error bars represent ± 1 standard error of the mean

How can the present results be reconciled with prior investigations of nature-related cognitive benefits (e.g., Emfield & Neider, 2014), which have claimed null effects of natural interventions, including natural sounds? Beyond the surface-level details in soundscape selection and the duration of the intervention, Emfield and Neider compared cognitive performance before and after participants experienced one of seven environment types. Six conditions were crossed in a 2 (environment: nature, urban) × 3 (modality: sounds, images, combined sounds and images) manner, while the seventh condition was a control. As such, the experiment did not focus on whether natural sounds *specifically* led to cognitive improvements relative to urban sounds (as these represented just two of the seven conditions and were never considered independently). Descriptively, the relative pre-post BDS improvement was highest when comparing nature and urban sounds (Emfield & Neider, 2014; Table 3), suggesting that the present results may be more consistent with prior investigations than initially presumed. Additionally, despite their design, Emfield and Neider did not specify factors related to environment or modality in their analyses, which may have reduced the sensitivity to detect nature-related improvements. Indeed, all three nature conditions showed greater BDS improvements compared to the urban conditions (Emfield & Neider, 2014; Table 3), raising the possibility that a model incorporating environment as a factor may have detected a time-by-modality interaction.

Although previous research has shown that interacting with nature has been shown to increase positive affect and decrease negative affect (e.g., McMahan & Estes, 2015), the present experiment did not demonstrate that experiencing natural versus urban soundscapes *differentially* influenced affect. This null

Table 1 Pre- and post-intervention scores for the computerized tasks

	Pre-Natural	Post-	ES	Pre-Urban	Post-	ES
Full (n = 63)						
PANAS PA	2.83 (0.57)	2.62 (0.73)	0.45	3.18 (0.84)	2.90 (0.80)	0.40
PANAS NA	1.91 (0.67)	1.67 (0.70)	0.70	1.73 (0.63)	1.65 (0.63)	0.17
BDS	9.74 (2.31)	10.61 (2.33)	0.45	9.00 (2.60)	8.94 (2.54)	0.03
DNB	1.49 (0.60)	1.77 (0.63)	0.67	1.49 (0.52)	1.56 (0.48)	0.17
Composite	-0.04 (0.83)	0.38 (0.81)	0.82	-0.19 (0.79)	-0.14 (0.79)	0.01
Naïve (n = 46)						
PANAS PA	2.86 (0.54)	2.56 (0.71)	0.58	3.15 (0.88)	2.91 (0.85)	0.36
PANAS NA	1.97 (0.65)	1.71 (0.72)	0.84	1.74 (0.64)	1.62 (0.63)	0.24
BDS	9.62 (2.33)	10.52 (2.80)	0.49	8.76 (2.77)	8.52 (2.65)	0.12
DNB	1.42 (0.62)	1.68 (0.61)	0.75	1.44 (0.53)	1.52 (0.49)	0.19
Composite	-0.02 (0.87)	0.37 (0.88)	1.01	-0.16 (0.81)	-0.14 (0.78)	0.05

Note: Values in parentheses represent standard deviations. The effect size (ES; Cohen's d) reflects the difference between pre- and post-intervention scores

effect was unlikely due to the in-lab administration of sounds in the present experiment, as previous work in this domain has found that nature sounds can facilitate mood recovery even when briefly administered in a laboratory setting (Benfield et al., 2014). However, there are two likely explanations for the discrepancy in these findings. First, unlike the experiment reported by Benfield and colleagues, the present experiment did not include an affective manipulation to decrease positive affect and increase negative affect; thus, participants' affective state in the present experiment may not have been as sensitive to the soundscape manipulation because there was no need to "recover" from an induced, unpleasant affective state. Related to this point, it is possible that an additional administration of the PANAS immediately *after* the cognitive tasks may have proven to be more sensitive, as the demanding nature of the cognitive tasks may have decreased positive affect and increased negative affect, which in turn may have allowed a nature-related change in affect to manifest. Second, the PANAS instructions in the present experiment asked participants to make their judgments based on how they felt "over the past few hours." This language may have created some confusion during the post-intervention administration, as a "few hours" would have encompassed a timespan that was much wider than the duration between PANAS administrations. Thus, the null PANAS findings can be likely explained by these particular choices in methodology rather than actual evidence for the absence of an effect.

Constraints on generality

The present results demonstrate an improvement in directed attention after hearing natural sounds compared to urban sounds, yet it is important to consider the potential constraints on how these results may generalize to different populations, testing environments, and procedures (see Simons, Shoda, & Lindsay, 2017).

ART suggests that nature can restore directed attention functioning through *soft fascination* (i.e., a soft capturing of involuntary attention), as this kind of state is thought to allow directed attention mechanisms a chance to rest and replenish (Kaplan, 1995). The theory does not outline broad constraints with respect to particular populations; thus, we would expect our results to generalize beyond the present sample in terms of age (e.g., generalizing to children and elderly adults) and geographic location. In conceptual support of this generalization, research has associated greenspace with academic performance in children living in Barcelona, Spain (Dadvand et al., 2015), as well as improved concentration among elderly individuals in Lund, Sweden (Ottosson & Grahn, 2005).

However, ART clearly outlines that soft fascination is a necessary, but not sufficient, condition for restoration. In addition to soft fascination, Kaplan (1995) proposes three additional considerations that may influence the degree to which a natural environment would facilitate attention restoration. First, an environment must promote the sense of "being away," which represents a conceptual (not necessarily physical) transformation. Thus, nature sounds may provide particular restorative benefits in contexts such as the present experiment (i.e., following difficult cognitive tasks) as they represent a conceptual shift in which the listener can simply listen without having to remember explicitly. Second, the environment must have *extent*, meaning that it must be sufficiently rich and engaging. While the presentation of nature in the present experiment was constrained, the use of headphones and relatively long (20-s) sound clips may have contributed to the nature sound's *extent*, facilitating restoration. Third, there needs to be *compatibility* between the environment and the individual's goals and desires, meaning an individual should not have to second guess or closely monitor their own behavior in the context of the environment. In this sense, providing aesthetic judgments of the sounds in the present experiment may have facilitated restoration, as such a task would keep listeners engaged but in a manner that is compatible with contemplation and reflection. We have no reason to believe that the results depend on other characteristics of the participants, materials, or context.

Conclusion

The present experiment furthers the understanding of ART through demonstrating that natural sounds, which have been previously shown to be perceived as restorative (e.g., Jahncke, Eriksson, & Naula, 2015; Ratcliffe et al., 2013), can improve directed attention in a similar manner to natural images (e.g., Berman et al., 2008). Furthermore, despite finding a clear aesthetic preference for natural sounds, aesthetic ratings were not significantly related to the observed cognitive benefits, which would have been consistent with SRT. These results further extend single-session, experimental tests of ART to a composite measure of directed attention that is more robust against task-specific strategies, which may ultimately provide a more accurate assessment of how nature may improve directed attention more generally.

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Compliance with ethical standards

Dedication The authors would like to dedicate this paper to [redacted] (1936–2018).

Declaration of Competing Interests [redacted]

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A synthesis of health benefits of natural sounds and their distribution in national parks

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Parks are important places to listen to natural sounds and avoid human-related noise, an increasingly rare combination. We first explore whether and to what degree natural sounds influence health outcomes using a systematic literature review and meta-analysis. We identified 36 publications examining the health benefits of natural sound. Meta-analyses of 18 of these publications revealed aggregate evidence for decreased stress and annoyance ($g = -0.60$, 95% CI = −0.97, −0.23) and improved health and positive affective outcomes ($g = 1.63$, 95% CI = 0.09, 3.16). Examples of beneficial outcomes include decreased pain, lower stress, improved mood, and enhanced cognitive performance. Given this evidence, and to facilitate incorporating public health in US national park soundscape management, we then examined the distribution of natural sounds in relation to anthropogenic sound at 221 sites across 68 parks. National park soundscapes with little anthropogenic sound and abundant natural sounds occurred at 11.3% of the sites. Parks with high visitation and urban park sites had more anthropogenic sound, yet natural sounds associated with health benefits also were frequent. These included animal sounds (audible for a mean of 59.3% of the time, SD: 23.8) and sounds from wind and water (mean: 19.2%, SD: 14.8). Urban and other parks that are extensively visited offer important opportunities to experience natural sounds and are significant targets for soundscape conservation to bolster health for visitors. Our results assert that natural sounds provide important ecosystem services, and parks can bolster public health by highlighting and conserving natural soundscapes.

noise | bird song | visitor experience | water sounds | stress

The sounds of nature have long generated powerful reactions in human beings—from inspiring music and poetry (e.g., Beethoven's Pastoral Symphony) to providing the stark symbolism that ignited the environmental movement (e.g., Rachel Carlson's Silent Spring). Sounds confer a sense of place, connect people to nature, and increasing evidence suggests that natural sounds are important for human health and well-being (1).

Soundscapes are the collection of sounds perceived in an environment, including those from biological sources (e.g., bird vocalizations), geophysical sounds (e.g., wind and rain), and anthropogenic sounds [including noise from road and air traffic (2)]. Soundscapes provide crucial information for both wildlife and humans (3). Many species rely on sound to communicate (4). Sound perception enables most species, including all known vertebrates, to surveil their surroundings. Thus, hearing causes behavioral and physiological responses to soundscapes [e.g., changes in heart rate regulated by the sympathetic nervous system (1)]. Natural soundscapes are increasingly threatened due to the rapid loss of sound-producing organisms [e.g., birds (5)] and intrusion of noise. Noise causes changes in behavior, physiology, and fitness in wildlife that can alter ecosystem functioning, further altering the natural acoustic environment (6). Noise masks natural sounds, interfering with important signals and altering the character of a soundscape. For humans, noise contributes to varied health problems, including hearing loss, nonauditory physiological effects, increased occurrence of hypertension and cardiovascular disease, and high levels of annoyance (7). Noise is present even in remote protected areas in the United States, and soundscape conservation is a burgeoning priority (8).

The health benefits of exposure to nature are well documented (for a recent overview, see ref. 9). Here, we define human health broadly, encompassing physiological outcomes (e.g., stress) and potential psychological precursors along the pathway to health outcomes [e.g., preference (1)]. Two psychological theories explain the mechanistic basis of the restorative effects of exposure to nature (including sound), drawing heavily from the theory of evolution (10). Attention Restoration Theory centers on the ability of nature to replenish attention through unconscious, cognitive processes (11). In contrast to the constant fatigue-inducing stimulation in urban environments, nature does not require directed attention and simultaneously elicits pleasure and relaxation. Stress Recovery Theory posits that nature may be perceived as less threatening and thus less arousing, leading to recovery from stress through autonomic response to nature (12). As such, conserving nature has considerable health implications particularly in increasingly urbanized populations, as exposure improves birth outcomes, mortality rates, mental health and stress, cognitive performance, and the rate of a myriad of diseases (reviewed in refs. 13, 14). While

Significance

This study examines evidence of the health benefits of natural soundscapes and quantifies the prevalence of restorative acoustic environments in national parks across the United States. The results affirm that natural sounds improve health, increase positive affect, and lower stress and annoyance. Also, analyses reveal many national park sites with a high abundance of natural sound and low anthropogenic sound. Raising awareness of natural soundscapes at national parks provides opportunities to enhance visitor health outcomes. Despite more abundant anthropogenic sound, urban and frequently visited sites offered exposure to natural sounds associated with health benefits, making them a valuable target for soundscape mitigation. Our analysis can inform spatial planning that focuses on managing natural soundscapes to enhance human health and experiences.

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the benefits of viewing nature are more studied, the influence of the acoustic environment is emerging as an important mechanism through which contact with nature affects human health (15). Audiovisual interactions play a significant role in perception, and there is often synergy between the influence of visual and acoustic exposure to nature on perception of environmental quality (16).

Historically, soundscapes have been investigated in the context of the deleterious effects of noise (17). Natural soundscapes play a central role in urban environmental sustainability because they offer reduced exposure to adverse effects of noise to which urban populations are highly exposed (18). Natural sounds have also been recognized for their ability to mask noise (19), their improvement of perceived park soundscape quality and park experience (20), their ability to enhance perceptions of the built environment (21), and their capacity for psychological restoration (22). Thus, research increasingly focuses on evaluating the characteristics of soundscapes by quantifying their different components (23) to manage soundscapes as a natural resource (24).

National parks have some of the most pristine soundscapes in the United States, yet noise is still widespread across the park system (25). Congressional concerns over the impact of noise have resulted in mandated protection of acoustic environments in US national parks (17). In parks, soundscapes are managed to minimize noise exceeding levels known to be detrimental to wildlife, visitor use, and cultural values (26). Natural sounds are increasingly recognized in law and policy as a park resource and have thus become a subject for conservation and restoration management (27). Here, we explore whether conserving natural soundscapes is also an opportunity to bolster public health. To determine whether and to what degree natural sounds influence health outcomes, we conduct a systematic literature review and meta-analysis. Given the evidence showing that natural sounds do influence health and to facilitate park soundscape management for public health, we then examine the distribution of natural sounds in relation to anthropogenic sound at 221 sites in 68 national parks. We enumerate different components of soundscapes identified to be particularly important for human health. Finally, we investigate soundscapes near urban areas and in relation to park visitation, acoustic environments which may be particularly important health resources for visitors.

Results

Systematic Review and Meta-Analysis. In our systematic review of peer-reviewed literature, only 19% of studies examining the health benefits of natural sounds (n = 7) measured traditional health outcomes, including heart rate, blood pressure, perceived pain, skin conductance, cortisol, and t-wave amplitude. Other studies examined the potential precursors along the pathway to health, including metrics of perception, mood, and cognitive performance. For 52% of outcomes measured (13 studies in the meta-analysis), we expected to see an increase due to natural sound (i.e., health and positive affect), and in the other 48% (12 studies in the meta-analysis), we expected to see a decrease due to natural sound (i.e., stress and annoyance).

Most studies (61%, n = 22) occurred in a laboratory or hospital setting rather than in the field. Research occurred in 11 different countries, with the largest number in Sweden (22%, n = 8). Studies had a mean sample size of 150.6 (±304.3 SD) and a mean quality score, based on the Quality Assessment Tool for Quantitative Studies, of 1.8 (±0.4 SD; *SI Appendix*, Fig. S1).

The overall mean effect size for health and positive affect outcomes was 1.63 (95% CI = 0.09, 3.16), corresponding to a 184% overall improvement in groups exposed to natural sounds relative to comparison groups (Fig. 1). The large variance in effect sizes was due to one study with particularly large effect sizes (28). The overall mean effect size for stress and annoyance outcomes was −0.60 (95% CI = −0.97, −0.23), corresponding to a 28% overall decrease in groups exposed to natural sounds relative to comparisons (Fig. 1).

We found significant heterogeneity between effect sizes in all models (Q > 248.4, P < 0.001), suggesting that moderators not considered in the model influenced the health benefits of natural sound exposure. We found no obvious pattern of publication bias in the funnel plot (*SI Appendix*, Fig. S1). If we only included studies with high quality scores (≤1.5), mean effect sizes of models were still significant (*SI Appendix*, Table S1).

Of the three types of natural sounds (birds, water, and mixed), we found that water sounds had the largest mean effect size for health and positive affect outcomes (2.01, 95% CI = 0.35, 3.67), and bird sounds had the largest mean effect size for stress and annoyance (1.11, 95% CI = −1.82, −0.4, Fig. 2). Yet, relatively few studies tested bird sounds explicitly (11 effect sizes in

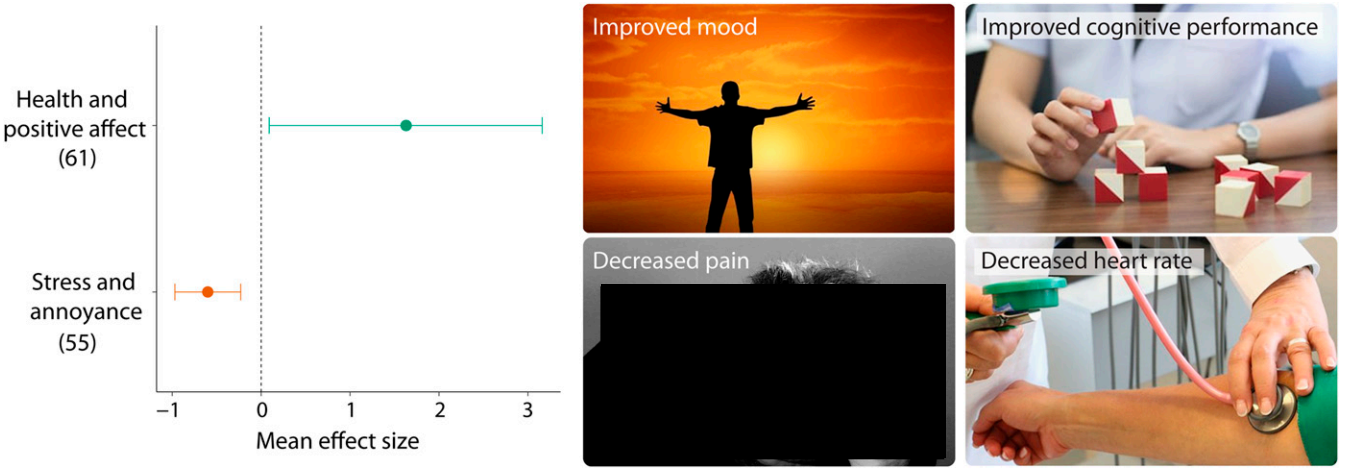


Fig. 1. Health and positive affective outcomes improved while stress and annoyance decreased in studies examining the benefits of exposure to natural sounds. Weighted mean effect sizes are from meta-analytic models of 18 studies, and the error bars indicate 95% CIs. A positive mean value (to the right of the dashed zero line) indicates health and positive affective outcomes improved in groups exposed to natural sound, and a negative value (to the left of the dashed zero line) indicates stress and annoyance indicators decreased in groups exposed to natural sound. Examples of metrics of health and positive affect included improved mood and cognitive ability, and metrics of stress and annoyance included decreased pain, heart rate, and blood pressure. All images are free for use, no attribution required.

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2 studies). Comparing natural sound and noise to noise had the largest mean effect size for health and positive affective outcomes (9.9, 95% CI = 8.46, 11.29), although only one study tested this effect. Comparing natural sound to noise had the largest mean effect size for both health and positive affective outcomes (1.7, 95% CI = 0.16, 3.24) and stress and annoyance (−0.81, 95% CI = −1.21, −0.40, Fig. 2). Comparing more natural sounds versus fewer natural sounds and natural sounds versus no sound also significantly improved health and positive affect and decreased stress and annoyance. The weakest contrast in our results was between natural sounds and natural sounds mixed with noise. Only one study tested the influence of more natural sounds versus fewer (11 effect sizes).

Sounds in US National Parks. Given the evidence that natural sounds influence health outcomes and that noise can diminish positive health benefits, we examined the prevalence and distribution of soundscapes with low anthropogenic sound audibility and high natural sound audibility in US national parks. Of the 221 acoustic monitoring sites analyzed, we found 75.1% (n = 166) had high audibility of biological sounds (i.e., audible >75% of time) and 40.7% of sites (n = 90) had a high audibility of geophysical sounds. As the most important sounds for health and positive affect identified in our review, we found bird sounds were audible 42.1% (mean ± 20.1 SD) of the time among sites and water related sounds were audible 22.8% (mean ± 36.2 SD) of the time among sites. Overall, 11.3% of sites (n = 25) had low audibility of anthropogenic sound (i.e., audible <25% of time) and high audibility of biological or geophysical sounds, sites which may represent important acoustic environments for human health (*SI Appendix*, Fig. S2). Additionally, 22.6% of sites (n = 50) had moderate audibility of noise (25 to 75%) and high audibility of biological or geophysical sounds (*SI Appendix*, Fig. S2).

Parks with more annual visitors (more than the median) had a higher average audibility of anthropogenic sound (mean ± SD: 0.81 ± 0.16) than those with fewer visitors (0.59 ± 0.34) but similar audibility of biological and geological sounds. Sites with high audibility of biological or geophysical sounds and low anthropogenic sound audibility had fewer visitors on average (370,420 ± 640,939 visitors per year) than those without (1,452,147 ± 2,640,973). Most sites with high audibility of biological or geophysical sounds and low anthropogenic sound audibility were located in Alaska, Hawaii, and the Pacific Northwest (Fig. 3) and were far from urban areas (Fig. 4). Only three sites with high audibility of biological or geophysical sounds and low anthropogenic sound audibility were within 100 km of urban areas (Fig. 4). Despite anthropogenic sound being audible most of the time (mean audibility ± SD: 90.2 ± 11.7), at recording sites within urban areas (n = 5), biological sounds were audible on average 59.3% of the time (±23.8 SD), and geophysical sounds were audible 19.2% of the time (±14.8 SD).

Discussion

Results from our systematic review and meta-analysis demonstrated that exposure to natural sounds improves health outcomes and positive affect and decreases stress and annoyance. These results align with many studies documenting the health benefits of exposure to nature through other sensory stimuli. Our review showed that natural sounds alone can confer health benefits. This finding can be interpreted from an evolutionary perspective, where humans attend to patterns that signal danger and security (29). Natural acoustic environments provide indications of safety or an ordered world without danger, allowing control over mind states, reduction in stress-related behavior,

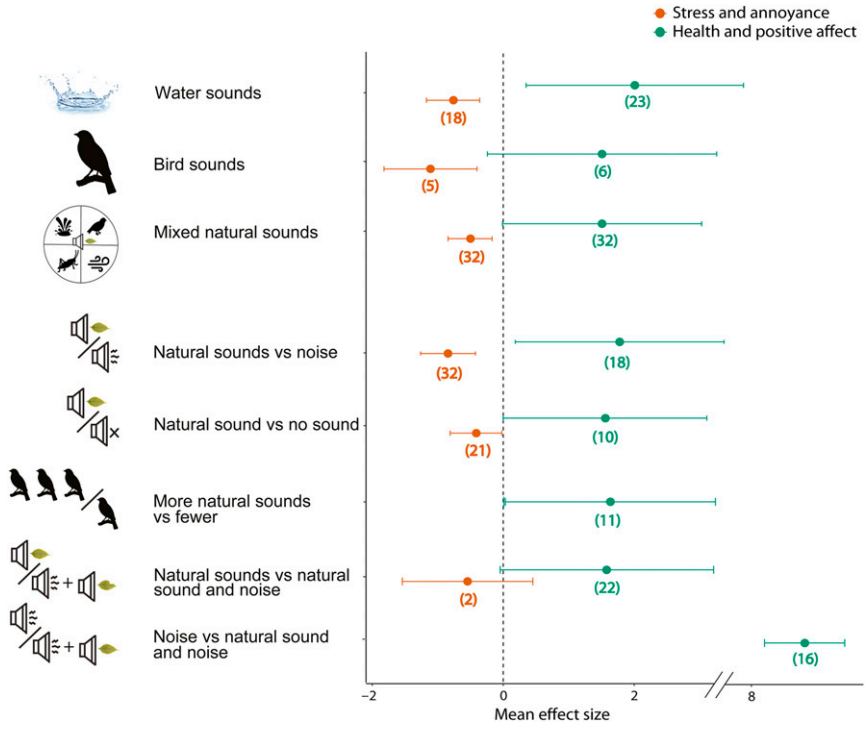


Fig. 2. Weighted mean effect sizes of natural sound on health and positive affective outcomes and stress and annoyance outcomes for different types of natural sounds and different treatment comparisons. Water sounds had the largest mean effect size for health and positive affective outcomes, bird sounds had the largest for stress and annoyance, and comparing natural sound to noise had the largest for health and positive affect and stress and annoyance. The error bars indicate 95% CIs. A positive mean value (to the right of the dashed zero line) indicates health and positive affective outcomes improved in groups exposed to natural sound, and a negative value (to the left of the dashed zero line) indicates stress and annoyance indicators decreased in groups exposed to natural sound. Part of the x-axis is removed for display purposes.

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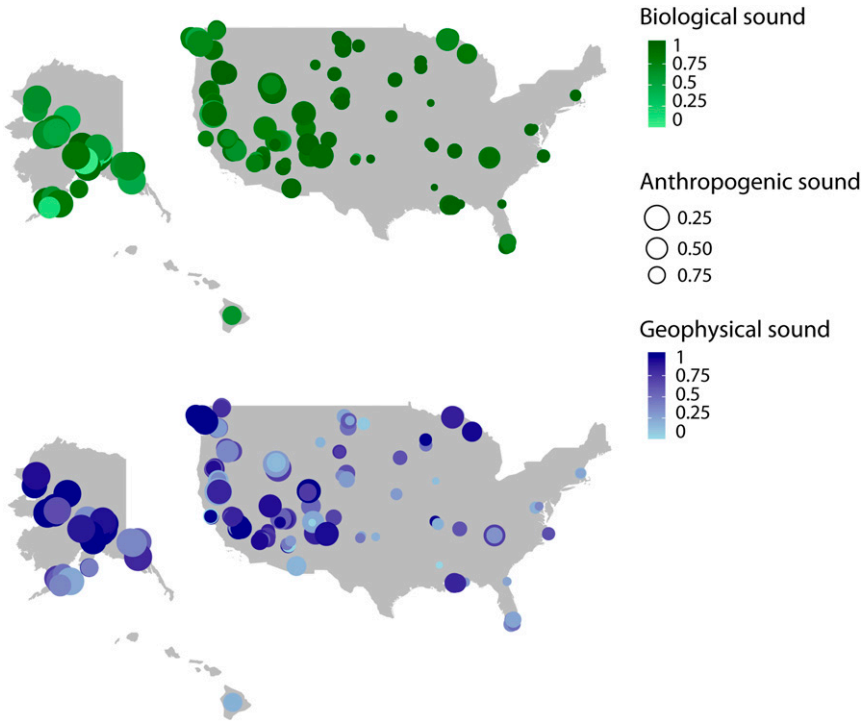


Fig. 3. The proportion of each type of sound (biological—sounds produced by animals; geophysical—sounds from water, wind, and weather; and anthropogenic—sounds produced by humans) observed in recordings collected in parks across the United States indicate acoustic environments important for human health—sites where natural sounds are more abundant (darker colors—higher audibility) and anthropogenic sounds are less abundant (larger circles—lower audibility). Audibility of sounds are predicted by generalized linear mixed models. Note that sites were not selected at random within parks or regions; they were selected to monitor specific settings of interest to park managers.

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and mental recuperation (30). Conversely, an absence of natural safety indicators in the acoustic environment may provoke vigilance and autonomically induce a more alert, aroused state. The demonstrated health benefits of exposure to natural sounds affirm the importance of including acoustic environments in valuations of ecosystem services (3).

Our meta-analysis indicated that water sounds had the largest effect on health and positive affective outcomes, while bird sounds had the largest effect on alleviating stress and annoyance, and both sounds were audible >23% of the time in park recording sites. The importance of water sounds may relate to the critical role of water for survival, as well as the capacity of continuous water sounds to mask noise. Water features have often been used as urban landscape elements to enhance acoustic environments (31). Not only can sounds from water mask noise, but they also increase the pleasantness and positive perception of urban greenspace (32). Bird song is also a widespread component of nature experiences and can restore attention, enhance mood, decrease perceived stress, and increase the familiarity and pleasantness of a soundscape (33).

Our analysis showed that exposure to natural sounds offers health benefits when compared with exposure to noise. In parks, noise degrades visitor enjoyment and health directly as an environmental stressor and indirectly by altering the number of sound-producing animals and thus decreasing the diversity of natural sounds (3, 34). However, the presence of natural sounds alongside noise in some instances can improve the perception of soundscape quality, promoting calmness and reductions in annoyance (35). Prominent, persistent natural sounds may confer additional health benefits by masking noise.

The majority of studies reviewed here occurred in laboratory settings; there was limited experimental evidence from the field. Furthermore, many intriguing findings were examined by limited numbers of studies. For example, there was only one study that examined outcomes of increasing numbers of bird species' song. Although participants preferred soundscapes with a higher richness of bird song (21), the link between soundscape diversity and health benefits remains understudied. Moreover, most of the research was conducted with Western populations and ethnicity was not reported. Therefore, future research could usefully explore differences in soundscape meanings, preferences, and health benefits across a more diverse sample. Finally, further research could account for relevant moderators, such as the company of others, fatigue, exposure duration, activities while outdoors, and demographics.

We found that 11.3% of analyzed recording sites in national parks had a low audibility of anthropogenic sound and had a high audibility of natural sounds, representing soundscapes that offer important health benefits. In addition to being a major motivation for visiting parks (36), these natural soundscapes represent important resources to be protected and enhanced for both ecological and social benefits (3).

Nature-based health interventions are increasingly numerous (37), including a growing number of community collaboration projects and a national park prescription program [www.parkrx.org/ (38)]. However, explicit consideration of the acoustic environment is rare in these initiatives. Ongoing soundscape monitoring in national parks provides ample opportunities to incorporate soundscape quality and enhance health outcomes for visitors. Innovative programs like "soundwalks," or any excursion whose main purpose is listening, could be used to enhance awareness and appreciation of natural soundscapes like those identified here (39). Understanding the distribution of health-benefiting soundscapes in relation to visitation can inform spatial planning and policy making for parks and communities (40). For example, although visitation was lower in parks with soundscapes with low audibility

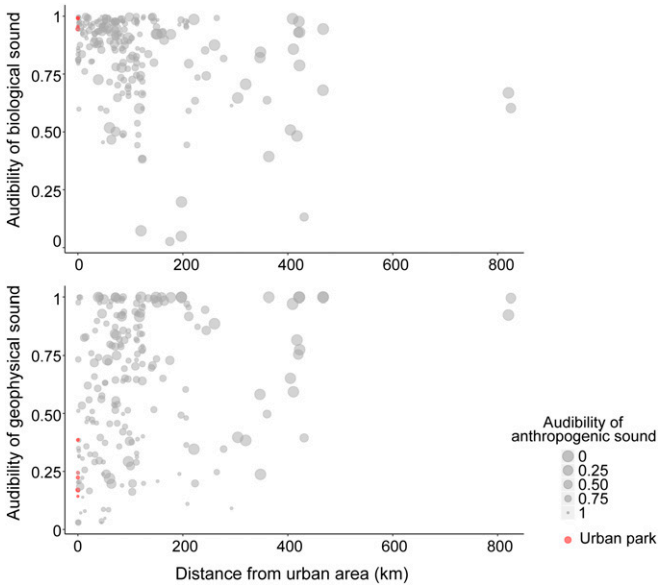


Fig. 4. Many US park sites near urban areas had a high proportion of recordings containing biological (*Top*—produced by animals) and geophysical (*Lower*—from water, wind, and weather) sounds but also high anthropogenic sounds (smaller points). Sites within urban areas (red) with high audibility of biological and geophysical sound could represent important acoustic environments important for the health of urban visitors. Audibility is the proportion of each type of sound observed in subsampled recordings collected in parks across the United States predicted by generalized linear mixed models.

of anthropogenic sound and high audibility of natural sounds, on average, over 370,000 people visit each of these parks per year. In these cases, signage identifying natural soundscapes can attract visitors to these health-benefiting sites, improve soundscapes by decreasing visitor noise (41), increase time spent in a park (42), and enhance visitor perceptions of sounds and the park (43). Additionally, noise management in parks with high visitation and high natural sound audibility can increase access to natural soundscapes (44) and their health benefits.

As human populations become increasingly urbanized, experiencing soundscapes rich in natural sound without noise will become ever more exceptional and important for enhancing the health of visitors. Our analysis shows that such sites are rarely near urban centers, with only three of these types of natural soundscapes found within 100 km of urban areas. However, biological and geophysical sounds were audible 59% and 22% of the time in urban parks on average. Although urban parks present formidable soundscape management challenges, restoring their soundscapes may produce the greatest health benefits. Nature-contact benefits can be most pronounced for low-income groups (45) whose travel options may be limited. We found 22.6% of urban park sites had high audibility of natural sounds and moderate audibility of anthropogenic sound. For these types of urban soundscapes, employing noise reduction tools (46) or soundscape augmentation (47) could produce widespread benefits for human health.

Soundscapes are important for public health, due to both the benefits of natural sounds and the adverse effects of noise. These benefits support an increasing policy focus on biodiversity conservation alongside human health (48). Moreover, awareness of the health benefits of nature will likely broaden and diversify public support because public opinion is most often driven by emotion and experience (49). Thus, the conservation of soundscapes in parks and other greenspaces has multiple benefits, including preserving important connections with nature, strengthening biodiversity conservation, and bolstering public health.

Materials and Methods

Systematic Review. To assess the empirical evidenceshowing the effect of natural sounds on human health, we systematically reviewed the literature. We searched Web of Science, PubMed, and Scopus for relevant publications using search terms that were broad enough to locate studies in a variety of disciplines which were then reviewed for inclusion (*SI Appendix*, Figs. S2 and S3 and the registered strategy with PROSPERO CRD42018095537). After selecting qualifying studies, bibliographies for each were examined for additional studies, yielding a total of 36 articles for inclusion.

To integrate information across studies, we extracted study site and design; the type of comparison groups (group exposed to natural sound versus no sound, natural sound versus noise, natural sound and noise versus noise, natural sound and noise versus natural sound, and more natural sounds versus fewer), the type of natural sound (water, bird, or mixed natural sounds), the mean and SD of health outcomes, and sample size in each group. Finally, we assessed study quality using the Quality Assessment Tool for Quantitative Studies (*SI Appendix*, Table S2).

Only 18 studies had enough information for further meta-analysis, involving calculation of effect sizes (Hedges' g) and fitting random-effects meta-analysis models in R version 3.5.2 [*SI Appendix*, Fig. S2 (51)]. We fitted models separately for health outcomes that were expected to improve (hereafter health and positive affective outcomes) or be reduced (hereafter stress and annoyance). To account for multiple comparisons and outcomes within a single study, study ID was included as a random factor in each model. To test for associations between effect size of health outcomes and attributes we extracted from studies, we used mixed-effects models with categorical moderators (i.e., type of comparison group and type of natural sound assessed). The small sample size necessitated simple models. Therefore, we tested each moderator in a separate model. Effect sizes were considered to be significantly different from zero when 95% CI did not overlap zero. We tested for heterogeneity by calculating the Q statistic for all models and examined publication bias using funnel plots of models without moderators (*SI Appendix*, Fig. S2). Finally, we carried out a sensitivity analysis to investigate the influence of study quality (*SI Appendix*, Fig. S2).

Sounds in US National Parks. To examine the distribution of natural sounds in national parks, we used the National Park Service Natural Sounds and Night Skies Division (NSNSD) nationwide acoustic dataset. Detailed methods of acoustic recording collection and analysis are outlined in Lynch, Joyce, and Fristrup (17) and Buxton et al. (25). Briefly, the NSNSD has been monitoring the acoustic environment since 2000. Trained technicians identified sounds to categories (anthropogenic, geophysical, and biological) by listening to and observing spectrograms of subsampled recordings at 221 sites in 68 parks (*SI Appendix*, Table S3).

Broad anthropogenic sound categories included aircraft, motorized vehicles, people talking, domestic animals, trains, and infrastructure maintenance (e.g., grounds care). We recognize that visitor conversation, laughter, and ranger interpretive sessions are intrinsic to park values and visitor experience. Yet, voices can also be noise in the context of experiencing natural sounds (44). It is worth noting that over 80% of anthropogenic sounds found in park recordings included transport-related noise (25), which has been shown to have deleterious effects on health. Geophysical sounds included wind, water, geothermal activity, and thunder; and biological sounds included those from insects, mammals, amphibians, and birds. These sound types were identified as present or absent in 10 s samples of audio taken continuously, or every 2 or 5 min (*SI Appendix*, Table S3). We calculated the audibility of sounds as the proportion of 10 s acoustic samples where a sound was observed during an hour of sampling.

To control for different seasons and years of acoustic recordings, we generated predictions of audibility using generalized linear mixed models. The most parsimonious model structure had a binomial error structure (*SI Appendix*, Fig. S2). All models incorporated year as a continuous variable and season and morning (7 to 9 AM) as dummy variables, with recording date nested within site nested within park as a random effect. Predicted audibility of biological, geophysical, and anthropogenic sounds were generated for summer, when biological (birds are still singing) and human (visitation peaks) sounds are high, in 2016 (highest percentage of recordings collected), in morning hours, to capture the dawn chorus. We compared the predicted audibility of geophysical, biological, and anthropogenic sounds with distance to an urban area with >50,000 people (52) and mean annual park visitation (53).

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Data Availability. All data have been deposited in Open Science Framework [redacted] 50) and/or are included in the *SI Appendix*.

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RESEARCH ARTICLE

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Urban green space soundscapes and their perceived restorativeness

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Abstract

1. The positive influence of urban green spaces on human health and well-being is well known while the pathways are little understood. Past research has largely focused on visual stimuli, yet the auditory pathway is also an important means for contact with nature.
2. The sonic environments of urban green spaces, however, are rarely entirely natural and many differ in their composition of natural sounds and anthropogenic noise. Few studies have investigated how these differences may impact the restorative potential of these soundscapes and, in particular, how the presence of traffic noise may constrain the benefits of natural sounds.
3. To address this gap, we examined differences in the perceived restorativeness and perceived restorative outcomes across a gradient of eight park soundscapes that differed in bird and traffic sounds. In a laboratory setting, 162 participants listened to sound samples and reported on perceptions of the soundscapes and restorative potential and outcomes.
4. The results strongly indicate that park soundscapes with a rich array of perceived bird sounds and minimal perceived traffic noise offer the greatest perceived restoration. Traffic noise was found to moderate the positive effect of bird sounds. The duration of time lived in the city and noise sensitivity were also positively associated with greater perceived restorative benefits while noise-sensitive people were also more negatively affected by traffic noise.
5. The promotion of highly natural soundscapes in urban green spaces and the reduction of traffic noise can provide nature-based solutions to human health and well-being in urban areas.

KEYWORDS
bird sounds, perceived restorativeness, soundscapes, traffic noise, urban parks

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1 | INTRODUCTION

With more than half of the world's population now residing in cities (United Nations, 2012), urban green spaces have become a principal means of contact with the natural environment for many people. The importance of such nature interactions has become well documented with a multitude of evidence demonstrating benefits to human health and well-being (Marselle et al., 2019), including improved cognitive function, recovery from stress and attention restoration (Berman et al., 2008; Bowler et al., 2010; Dean et al., 2019; Fuller et al., 2007; Hartig et al., 2014; Hartig & Staats, 2004; Kaplan & Berman, 2010; Marselle et al., 2019; Scopelliti & Vittoria Giuliani, 2004; Shin et al., 2010).

While much of this research on nature-health effects has often used visual stimuli as a focus (e.g. Carrus et al., 2013; Conniff & Craig, 2016; Staats & Hartig, 2004), sound is also an important pathway through which the environment is perceived by humans and can have direct influence over quality of life and physical well-being (Chuengsatiansup, 1999; Frumkin et al., 2017; Öhrström et al., 2006; Yang & Kang, 2005). In recent years, research has explored the restorative potential of natural sounds, commonly employing a soundscape approach which describes the sonic environment of a given area from a human perspective (Schafer, 1994). Such studies have typically used bird calls as a focus of natural sounds (Ratcliffe et al., 2013). In addition to being perceived as pleasant and relaxing (Payne, 2013), bird sounds have been shown to offer potential for stress recovery (Alvarsson et al., 2010) and attention restoration (Krzywicka & Byrka, 2017; Payne, 2013; Ratcliffe et al., 2013).

While urban parks are a source of natural sounds, their soundscapes also commonly include anthropogenic noise, such as vehicle and air traffic, which often dominates surrounding urban areas (Liu et al., 2013; Raimbault et al., 2003). Indeed, studies have shown birdsongs and vehicle traffic are the two principal sounds within parks recognised by park visitors (Szeremeta & Zannin, 2009). Evaluations of traffic noise within Brazilian and Italian city parks have indicated levels exceed city guidelines in a majority of parks (Brambilla et al., 2013; Szeremeta & Zannin, 2009). This is important as the negative effects of traffic and other anthropogenic noise are well established. Prolonged exposure to unwanted sounds is associated with a wide variety of health disorders, including annoyance, sleep disruption, fatigue, hypertension, heart disease and mental health disorders (Berglund et al., 2000; WHO, 2011).

Although studies have compared distinct natural and urban soundscapes, showing greater psychological restoration for natural soundscapes (Abbott et al., 2016; Krzywicka & Byrka, 2017; Payne, 2013), few studies have considered how varying degrees of both bird and traffic sounds *within* parks may influence restorative qualities and outcomes. In particular, we are interested in the interaction of positive and negative effects of soundscapes, that is, the extent to which vehicle traffic noise may diminish the restorative benefits of bird sounds. Currently, research in this area is somewhat unclear, with Suko et al. (2019) finding faint traffic noise mixed with bird songs, had a physiological impact but no effect on psychological restoration. As urbanisation continues to place pressure on existing urban and peri-urban green spaces (Fuller & Gaston, 2009), maintaining or creating diverse ecosystems within urban or peri-urban parks can constitute a critical investment in improving the quality of life of citizens (Dean et al., 2011). It is therefore important to develop insights into the therapeutic value of urban and peri-urban green space soundscapes and to identify how anthropogenic noise might confound this benefit.

1.1 | Theoretical frameworks

Much of the theoretical understanding for the mechanisms behind the restorative and stress recovery potential of green spaces are grounded in two frameworks: Attention Restoration Theory (Kaplan & Kaplan, 1989) and the Stress Reduction Theory (Ulrich, 1983). Attention Restoration Theory (ART) contends that cognitively demanding tasks result in directed attention fatigue but natural environments can facilitate the restoration of directed attention (Kaplan, 1995). Restoration of directed attention fatigue requires person–environment transactions in which a person experiences the following four qualities: *Fascination*, *Being Away*, *Compatibility* and *Extent* (Kaplan & Kaplan, 1989). *Fascination* refers to an environment's ability to capture attention effortlessly, such as, 'strange things, wild animals, bright things, pretty things, etc.' (James, 1985). *Being-Away* refers to the experience of physical or psychological distance to one's everyday routine. *Compatibility* describes the extent to which the environment's features align with the individual's intended activity in that space. *Extent* refers to the scope of the environment and its ability to provide explorative potential. The greater these four qualities are experienced by an individual, the greater the potential of the environment to facilitate attention restoration (Kaplan, 1995). Natural environments are theorised to have a high level of these four restorative qualities (Kaplan & Kaplan, 1989; Kaplan, 1995) and studies have demonstrated that bird sounds are associated with attention restoration (Ratcliffe et al., 2013).

Stress Reduction Theory (SRT) asserts that positive appraisals and interactions with nature can provide physiological benefits resulting in a reduction of stress and a shift towards relaxation and positive mood change (Ulrich, 1983; Ulrich et al., 1991). These positive changes are referred to as restorative outcomes (Ulrich et al., 1991). Evidence has shown that visiting green spaces, such as parks and forests, can provide these restorative benefits (Hartig et al., 2003). Within a soundscape context, we hypothesise that natural soundscapes containing a high degree of bird sounds may facilitate these restorative outcomes (Alvarsson et al., 2010).

The concept of constrained restoration (Hartig et al., 2007; von Lindern et al., 2016) contends that restoration may sometimes be impaired by certain environmental conditions. Hartig et al. (2007) explored this concept in a study in which cool summer weather served as an environmental condition which caused people to stay indoors more often, which, in turn, limited their exposure to restorative outdoor environments, thus constraining restoration. Anthropogenic

sounds such as traffic noise may constrain restoration benefits associated with bird sounds. Although Suko et al. (2019) found that bird songs with and without low traffic noise displayed no significant difference between perceived restorativeness scores, they did not examine the effect of varying levels of traffic noise. We hypothesise that as traffic noise is more strongly perceived among bird sounds, the beneficial effects of these soundscapes will be increasingly constrained.

Several environmental characteristics, such as the perceived naturalness of the soundscape and perceptions of bird species richness may also influence the restorative potential of soundscapes. For example, Carrus et al. (2013) found that as photos of parks were perceived to be more natural, perceived restorativeness increased, and a similar effect may occur in soundscapes. Additionally, personal factors such as noise sensitivity, environmental knowledge and familiarity with local birds may also be important. Noise sensitivity refers to people who react more strongly and negatively to elevated levels of noise than a typical person (Stansfeld, 1992). Such people may be more negatively impacted by traffic noise or, conversely, derive more benefit from a natural soundscape (Okokon et al., 2015). Knowledge of local birds may influence the ability to perceive bird sounds and species richness, a factor found to be important by Dallimer et al. (2012) in gauging levels of biodiversity. The amount of time lived in the city may also be a consideration, potentially influencing a greater sense of place attachment or familiarity of local birds which may lead to more positive perceptions of birds (Terzano & Gross, 2020). As such, we include these personal factors as confounders in our analyses.

1.2 | The current study

In the current study, our goal was to assess the influence of perceptions of bird and traffic sounds and overall naturalness on perceived restorativeness and perceived restorative outcomes. For this, we examined differences between eight different park soundscapes in a controlled laboratory setting along with moderating variables, such as noise sensitivity, environmental knowledge and the amount of time lived in the city.

Specifically, we addressed the following questions: (a) Do perceived restorativeness and perceived restorative outcomes vary in park soundscapes differing in perceived bird and traffic sounds? (b) How do perceived restorativeness and perceived restorative outcomes vary with perceived awareness, volume and pleasantness of bird calls and traffic sounds? (c) Do perceived traffic sounds constrain restoration by moderating the effect of perceived bird pleasantness on perceived restorativeness and perceived restorative outcomes? (d) How do perceptions of environmental characteristics of the soundscapes influence perceived restorativeness and perceived restorative outcomes? (e) Do noise sensitivity, environmental knowledge and the amount of time lived in the city moderate the effect of bird calls on perceived restorativeness and perceived restorative outcomes?

2 | METHODS

2.1 | Study area

Soundscape recordings were made in parks within the Brisbane Local Government Area (LGA) in southeast Queensland, Australia. With just over 1 million residents, Brisbane (27°28′S, 153°07′E) covers an area of 1,378 km^2 and Brisbane City Council maintains over 2,000 parks (ABS, 2016, BCC, 2020). These range in size from small suburban parks to urban and peri-urban forest bushland reserves (BCC, 2020).

2.2 | Site selection and park recordings

We aimed to capture a range of soundscapes commonly experienced by park users. Consequently, we recorded at sample sites along a gradient of low to high bird species richness and activity within the recordings and varying degrees of traffic noise. A single recording sample point was used 150 m along from the start of a main walking path or trail for each park which provided a location commonly used by park users and removed from the park boundary. Recordings were taken for 5 min between 6.30 and 7.30 a.m. on week days, an hour with bird activity, morning traffic and when parks are frequented by pre-work walkers/exercisers and commuters. All recordings were conducted during May to July 2019 in clear weather conditions using a Song Meter 4 acoustic recorder held at shoulder height (approximating the height of human ears).

From each 5-min recording, a 70-s sample was derived and for each 70-s sound sample a measure of bird and traffic sounds were obtained. Bird sounds were measured with species richness and a 'bird activity' score (Table S1). Bird species were identified manually by bird calls within the recordings with the process randomised and repeated to improve accuracy. Bird activity was obtained by ascribing a 'bird activity' score (using a five point scale of 1 = *Very low* to 5 = *Very high*) for every 5-s interval of each recordings. The mean score was taken as the bird activity score (A. Truskinger, personal communication, May 5, 2019). An indicator of traffic sound was derived by measuring the maximum A-weighted volume (dB) in the low level frequency of 25–500 Hz (similarly used by Suko et al., 2019) (Table S1). In the decibel scale, a 3db increase represents twice the sound pressure energy (sound intensity level), while in psychoacoustic terms, an approximately 10 db increase equates to twice the perceived loudness of a sound (Vic Roads, 2013).

To satisfy the repeated measures research design (see Section 2.3 below), eight sites were selected, using measures of bird species richness, bird activity and traffic noise volume (Figure 1). The eight sites were selected to provide a gradient of park soundscape samples that ranged from Sample 1: high traffic noise and very low bird activity/species richness, to, Sample 8: very low traffic noise and high bird activity/species richness. As such, the soundscape of Sample 1 was dominated by a high level of traffic noise with few bird sounds and contained only two species within the recording while Sample 8 had no traffic noise and comprised almost entirely bird sounds with seven



FIGURE 1 Overview of the eight parks in Brisbane, Australia. Sound samples recorded between 6.30 and 7.30 a.m. on week days. Brisbane CBD = Central Business District

species identified. Samples 2–7 provide a broad gradient between Sample 1 and Sample 8, with decreasing traffic noise and increasing bird activity and species richness within their soundscape samples. An inverse relationship between biophony (e.g. bird sounds) and anthrophony (e.g. traffic noise) is often found in soundscapes, whereby as one increases the other tends to decrease (Joo et al., 2011); this trend was observed in these soundscape samples.

2.3 | Experimental design and procedure

A repeated measures within subjects design was employed in which each participant listened to all eight sound samples, consistent with similar studies (e.g. Benfield et al., 2018; Krzywicka & Byrka, 2017). A laboratory setting was favoured over an in-situ approach for its ability to remove the influence of visual surrounding, isolate the audio pathway and control for potentially moderating factors, such as reason and duration of use of green spaces by visitors (Benfield et al., 2018; Payne, 2008).

Participants were University of Queensland students enrolled in first year psychology courses, recruited from the School of Psychology research participation programme. Participants received 1 credit point for taking part in the study; no monetary reimbursement was provided. At the start of the study, participants were provided with a brief written description of the procedure which outlined they were about to listen to eight different sound recordings from different Brisbane parks. Participants were instructed to close their eyes prior to listening to each sound recording. No accompanying visual stimuli of parks were provided, such that we could exclusively assess perceptions of sounds without confounding analyses.

All eight 70-s sound samples were played to participants in a randomised order. After listening to each sound sample, participants completed an identical block of questions relating to perceptions of the soundscape, perceived restorativeness and perceived restorative outcomes (Figure 2, see Supplementary Material for survey). To alleviate participant fatigue, two 1-min breaks were built in, after the third sample and again after the sixth sample. After listening to the eighth sound sample, the survey concluded with several items assessing participant characteristics, including age, gender, the amount of time (years) lived in Brisbane and whether the participant was born in Australia.

The survey was completed online using identical Microsoft Surface Pro tablets and Audio-Technica headphones set at a consistent volume. A quiet partitioned room was used with a maximum of four participants per survey session. The survey was conducted in accordance with approved guidelines and following Institutional Human Research Ethics Approval by the University of Queensland (Approval #2019001046). Participants provided informed written consent.

2.4 | Sample characteristics

In total, 162 participants took part in the study with almost three-quarters (74.1%) female and an average age of 20 years (M = 19.86, SD = 2.17). Just over half of participants were born in Australia (54.9%). Almost half of participants (49.4%) had lived in Brisbane for less than 3 years, and, of that group, almost a third (30.1%) for a year or less. Less than half (39.0%) of participants reported living in Brisbane for more than 10 years.

2.5 | Measures

2.5.1 | Outcome variables

Perceived Restorativeness was evaluated using a short-form of the 14-item Perceived Restorative Soundscape Scale (PRSS; Payne, 2013). For this study, we developed an abridged 5-item version of the Perceived Restorative Soundscape Scale—Short Form (called the PRSS-SF) by selecting the five items of the Perceived Restorative Scale by Berto (2005) but using the language and phrasing of the PRSS. These five items assessed the four restorative qualities of ART and were rated on a 7-point Likert scale (1 = Not at all, 7 = Completely). The mean of the following five items was used to create a Perceived Restorative score (range: 1–7, Cronbach's α = 0.91):

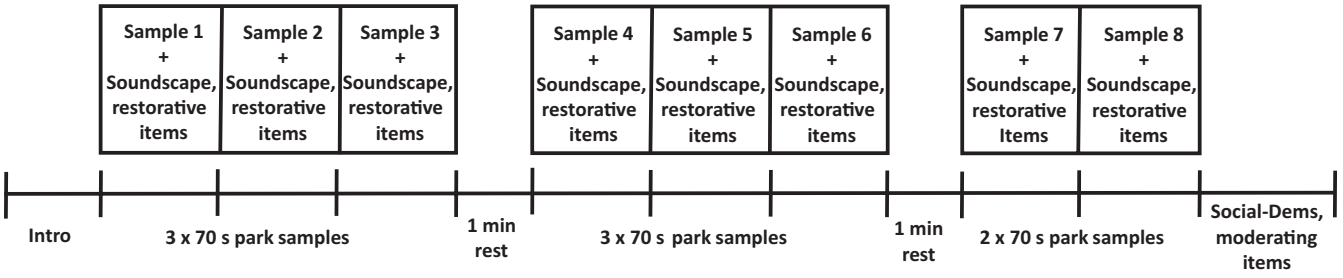


FIGURE 2 Overview of experimental procedure. After a short explanatory introduction, each participant listened to all eight sound samples in random order. After listening to each sample, participants answered questions relating to soundscape, perceived restorativeness and perceived restorative outcomes. Sound samples were presented in two blocks of three, and one block of two. Two 1-min rest periods occurred after the completion of the third and sixth sound samples. Covariate and moderating items were completed after the listening to the final sound sample

- *Fascination*—1 item (‘*The sounds in the recording have fascinating qualities*‘)
- *Being-Away*—1 item (‘*The sounds in the recording give me a good break from my day-to-day routine*’)
- *Compatibility*—2 items (‘*The sounds in the recording seem to fit together quite well*’,
- ‘*The sounds in the recording relate to activities I like to do*’)
- *Extent*—1 item (‘*The sounds in the recording suggest there is much to explore and discover*’)

Perceived Restorative Outcomes from listening to the soundscapes were measured with the 6-item Restorative Outcomes Scale (ROS; Korpela et al., 2008). The outcomes assessed are related to both ART and SRT: attention restoration, clearing one's thoughts, and relaxation and calmness. The wording of items on the ROS was adapted in this study to focus on perceived sounds rather than experience of a physical place (e.g. ‘I feel calmer after being here’ became ‘I feel calmer after listening to this recording’) The mean of the following six items was used to create a Perceived Restorative Outcomes score (range: 1–7, Cronbach's $\alpha = 0.94$):

- *Attention Restoration*—1 item (‘*My concentration and alertness clearly increases after listening to these sounds*’)
- *Clearing One's Thoughts*—2 items (‘*I can forget everyday worries listening to these sounds*’ and ‘*Listening to these sounds is a way of clearing and clarifying my thoughts*’)
- *Relaxation and Calmness*—3 items (‘*I feel calmer after listening to these sounds*’, ‘*After listening to these sounds I feel restored and relaxed*’ and ‘*I get new enthusiasm and energy for my everyday routines after listening to these sounds*’)

2.5.2 | Predictor variables

After listening to each sound sample, participants rated their perceptions of each of the following categories of sound: (1) Vehicle traffic, (2) Bird songs/calls, (3) Other natural sounds, (4) Voices/people talking and (5) Other (open-ended).

For each type of sound, participants rated perceived awareness, volume and pleasantness:

Perceived Awareness of each sound category in each sound sample was assessed with a single item (‘*I was aware of the following sounds in the recording*’) using a 7-point Likert scale (1 = *Not at all*; 7 = *Completely*) (Payne, 2008).

Perceived Volume of each sound category in each sound sample was assessed with a single item assessed (‘*Please rate how quiet or loud the following sounds seem to you in the recording*’) on a 7-point semantic differential scale (1 = Very quiet, 7 = Very loud), with an additional option (‘*I didn't hear this sound*’) (Payne, 2008).

Perceived Pleasantness of each sound category in each sound sample was assessed with a single item (‘*Please rate how unpleasant/pleasant you found the following sounds in the recording*’) on a 7-point semantic differential scale (1 = *Very unpleasant*, 7 = *Very pleasant*), with an additional option (‘*I didn't hear this sound*’) (Payne, 2008).

Perceived Bird Species Richness was assessed with a single item (‘*About how many different types of birds would you say you can hear in these recordings?*’) using a 4-point scale (0 = *None at all*, 1 = *1–3 types*, 2 = *4–6 types* and 3 = *7–10 types*). Items and response options were drawn from Fuller et al. (2007).

Perceived Tree Cover was assessed with a single item (‘*Based on the sound recording, about how many trees would you say are in the park?*’), utilising a 4-point scale (0 = *None at all*, 1 = *Some*, 2 = *Quite a lot* and 3 = *Lots*). Items and response options were adapted from Fuller et al. (2007).

Overall Naturalness was assessed with a single item (‘*Overall, how would you rate the naturalness of the sounds in the recording you just listened to?*’) on a 10-point semantic differential scale (1 = *Not natural at all*; 10 = *Completely natural*), adapted to focus on sounds from Carrus et al. (2013).

2.5.3 | Moderators and covariates

Several moderating variables were also assessed:

Noise Sensitivity was assessed with three items (‘*Noises get on my nerves and get me irritated*’, ‘*I'm good at concentrating no matter what is*

going on around me' (reverse scored) and '*I am sensitive to noise*' on a 7-point Likert scale (1 = *Not at all*; 7 = *Completely*) (Weinstein, 1978). A mean of these three items was used to create a 'Noise Sensitivity' score (Cronbach's $\alpha = 0.84$).

Bird wildlife knowledge was assessed using a methodology based on Dallimer et al. (2012) in which participants were asked to identify (by common name) 10 photos of common birds in the South East Queensland area. These were coded 0 = *Incorrect*, 1 = *Correct* and a summed count was used to create a 'Bird wildlife knowledge' score.

Time Lived in Brisbane was assessed by asking participants to enter (rounding to the nearest whole year) the number of years of they had lived in Brisbane city.

The survey concluded with covariate socio-demographic items, including gender, age and whether the participant was born in Australia.

2.6 | Statistical analysis

All data analyses were carried out with R Studio V1.2. To answer research question (a) and test for significant differences across the eight park sound samples on perceived restorativeness and perceived restorative outcomes, nonparametric one-way (Kruskal–Wallis *H* test) ANOVA tests were performed. This was selected instead of a parametric one-way ANOVA because the distribution of both outcome variables, perceived restorativeness and perceived restorative outcomes, failed Shapiro–Wilk tests for normality ($p < 0.001$ for both outcome variables). The sample size in the study was also sufficiently large to justify a nonparametric one-way ANOVA test, given that there were $N = 162$ responses for each of the eight groups (Fan et al., 2011). Subsequent post-hoc tests (Tukey HSD) were used to assess significant pairwise differences among park samples.

Pearson's correlation coefficient scores were calculated for all variables of interest to determine inclusion/exclusion for models. Perceived bird awareness and perceived bird volume were found to be strongly correlated ($r > 0.7$; Dancey & Reidy, 2007). Similarly, perceived traffic awareness and perceived traffic volume were also strongly correlated ($r > 0.8$; Dancey & Reidy, 2007). Perceived bird awareness and perceived traffic awareness were both excluded. Perceived volume variables (bird and traffic) were further explored and selected over perceived awareness variables as perceived volume had been consistently used in similar past studies as a predictor variable of perceived restorativeness of soundscapes (Payne et al., 2008). Perceived naturalness and perceived tree cover also displayed a moderate correlation ($r > 0.6$; Dancey & Reidy, 2007), with only perceived naturalness used in later analyses. Perceived naturalness was selected as it was considered a more important predictor variable, previously positively associated with perceived restorativeness in a visual context of parks by Carrus et al. (2013).

To assess the effect of predictor variables of interest on perceived restorativeness and perceived restorative outcome, mixed models were constructed, which allow the inclusion of both fixed and random effects (Fischer et al., 2011). Fixed effects included all predictor variables while random effects accounted for variation among participants and sound samples.

Mixed models were fitted using either perceived restorativeness or perceived restorative outcomes as dependent variables, with perceptions of the soundscape (perceived bird volume, perceived bird pleasantness, perceived traffic volume and perceived traffic pleasantness) and perceptions of environmental characteristics (perceived bird species richness and perceived naturalness) as fixed effects (predictor variables). Moderating effects were examined using the variables noise sensitivity, environmental knowledge and years lived in Brisbane. Random effects accounted for differences in the intercepts of participant responses and sound samples. Covariates included age, gender and whether the participant was born in Brisbane.

For each dependent variable (perceived restorativeness and perceived restorative outcomes), five models were conducted:

1. Model 1 addressed research question (b) and examined the effect of *perceived bird volume*, *perceived bird pleasantness*, *perceived traffic volume* and *perceived traffic pleasantness*.
2. Model 2 addressed research question (c) and examined the effect of the same predictor variables in Model 1 while also testing for an interaction between *perceived traffic volume* and *perceived bird pleasantness* to investigate constraint to restoration.
3. Model 3 addressed research question (d) and examined the effect of *perceived bird species richness* and *perceived naturalness*.
4. Model 4 further assessed research questions (b) and (d) and examined the effect of all soundscape perception variables from Model 1 with the perceived environmental characteristic variables (*perceived bird species richness* and *perceived naturalness*).
5. Model 5 addressed research question (e) with a complete model that included the same predictor variables in Model 4, along with all moderating variables (*noise sensitivity*, *time lived in Brisbane* and *bird wildlife knowledge*). For this model, iterative model reduction was performed using the lowest Akaike information criterion (AIC) (Akaike, 1974) to identify the optimal structure of the final model.

All five models were assessed for and met normality of residuals. No multicollinearity among independent variables was detected (variance inflation factor (VIF) < 2.5). All models were run with and without covariate variables which were not found to be significant factors in any models.

3 | RESULTS

3.1 | Perceived restorativeness (PRSS-SF) and perceived restorative outcome (ROS) scores across sound samples

Mean perceived restorativeness scores differed significantly between park samples ($p < 0.001$). Post-hoc tests revealed significant pairwise differences between the majority of sample scores, with only samples 6 and 7 and samples 3, 4 and 5 displaying no significant

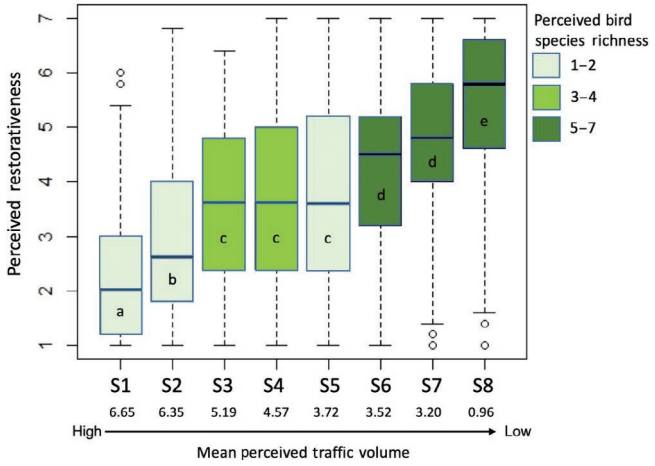


FIGURE 3 Boxplots of perceived restorativeness (PRSS-SF) for each sound sample, ordered by mean perceived traffic volume scores (highest to lowest) and colour-coded by perceived bird species richness. Letters denote significant ($p < 0.05$) differences between sound samples. Greater PRSS-SF scores indicate higher perceived restorative qualities in soundscapes. Sound sample S1 = highest objective traffic noise + low objective bird sounds, S8 = highest objective bird activity and species richness + no traffic noise, S2–S7 = decreasing objective traffic noise + increasing bird activity and species richness

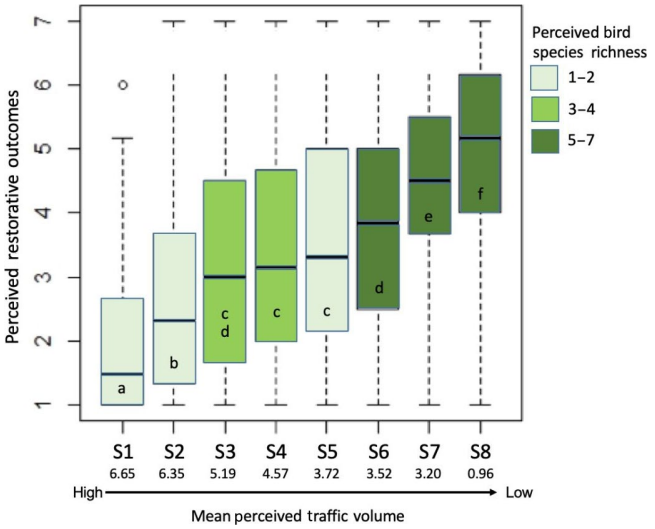


FIGURE 4 Boxplots of perceived restorative outcomes scores (ROS) for each sound sample (S), ordered by mean perceived traffic volume scores (highest to lowest) and colour-coded by perceived bird species richness. Letters denote significant ($p < 0.05$) differences between sound samples. Greater ROS scores indicate higher perceived restorative outcomes in soundscapes. Sound sample S1 = highest objective traffic noise + low objective bird sounds, S8 = highest objective bird activity and species richness + no traffic noise, S2–S7 = decreasing objective traffic noise + increasing bird activity and species richness

pairwise differences (Figure 3). Results demonstrate a clear gradient of increasing perceived restorativeness scores as perceived traffic volume decreases and perceived bird species richness increases (Figure 3). Perceived bird species richness was also moderately correlated with actual bird species richness within park sample recordings ($r = 0.59$; Table S2).

Perceived restorative outcomes scores were highly correlated with perceived restorativeness scores ($r = 0.89$) and showed similar significant differences across samples ($p < 0.001$). Post-hoc tests revealed significant pairwise differences between most samples (Figure 4). Results show increasing perceived restorative outcomes scores with decreasing perceived traffic volume and increasing perceived bird species richness (Figure 4).

3.2 | Mixed models analyses

The first model examined the influence of perceived soundscape factors on perceived restorativeness and perceived restorative outcomes. Overall, the four fixed effect perceived soundscape variables explained 35% of the variance in perceived restorativeness (Table 1). Perceived bird pleasantness ($p < 0.001$), perceived bird volume ($p < 0.001$) and perceived traffic pleasantness ($p < 0.001$) were all positively associated with perceived restorativeness scores. Perceived traffic volume ($p < 0.001$) had a negative impact on perceived restorativeness scores. For perceived restorative outcomes, the four fixed effect perceived soundscape variables explained 35% of the variance (Table 1). Similarly, perceived bird pleasantness, perceived bird volume and perceived traffic pleasantness were associated with higher perceived restorative outcomes scores while perceived traffic volume had a negative influence on perceived restorative outcomes (Table 2).

The second model tested the constraint to restoration hypothesis by examining the moderating role of perceived traffic volume on the relationship between bird sounds and restoration scores. This revealed that perceived traffic volume negatively moderates the positive effect of perceived bird pleasantness on perceived restorativeness ($p = 0.002$). Differences in the intercepts of each sound sample illustrate lower perceived restorativeness scores as perceived traffic volume increases (Figure 5; Table 1). When perceived traffic volume is high, the influence of perceived bird pleasantness on perceived restorativeness is reduced (Figure 5). The same effect was found when the model was repeated with perceived restorative outcomes as the dependent variable (Table 2).

The third model explored the effect of perceived bird species richness and perceived naturalness on perceived restorativeness and perceived restorative outcomes and explained 44% of the variance in perceived restorativeness scores. Perceived bird species richness and perceived naturalness were significantly associated with higher perceived restorativeness scores (Table 1) and higher perceived restorative outcomes scores (Table 2).

The fourth model combined soundscape perception variables (model one) and perceived environmental variables (model three). For perceived restorativeness, all four soundscape perception variables, as well as perceived naturalness ($p < 0.001$) and perceived bird species richness ($p = 0.044$) were significant (Table 1). For perceived restorative outcomes, all four soundscape perception variables and perceived

TABLE 1 Summary of multiple regression models (regression coefficients, standard errors and *p* values) for the outcome variable perceived restorativeness of soundscape (PRSS-SF)

Dependent variable: Perceived restorativeness of Soundscape (PRSS-SF)															
	Perception of soundscapes (Model 1)			Perception of soundscapes + Moderators (Model 2)			Perception of env. characteristics (Model 3)			Perception of soundscapes + env. characteristics (Model 4)			Perception of soundscapes + env. characteristics + moderators (Model 5)		
	B ± *SE*	95% CI	*p*	*B* ± *SE*	95% CI	*p*	*B* ± *SE*	95% CI	*p*	*B* ± *SE*	95% CI	*p*	*B* ± *SE*	95% CI	*p*
Perceived bird volume	0.24 ± 0.02	0.19, 0.29	**<0.001*****	0.24 ± 0.03	0.19, 0.29	**<0.001*****				0.11 ± 0.02	0.07, 0.16	**<0.001*****	0.13 ± 0.02	0.08, 0.17	**<0.001*****
Perceived traffic volume	−0.23 ± 0.02	−0.27, −0.19	**<0.001*****	0.006 ± 0.07	−0.20, −0.01	0.93				−0.11 ± 0.02	−0.15, −0.08	**<0.001*****	0.10 ± 0.06	−0.03, 0.22	0.11
Perceived bird pleasantness	0.25 ± 0.02	0.20, 0.29	**<0.001*****	0.40 ± 0.05	0.26, 0.42	**<0.001*****				0.17 ± 0.02	0.12, 0.21	**<0.001*****	0.26 ± 0.04	0.19, 0.33	**<0.001*****
Perceived traffic pleasantness	0.17 ± 0.02	0.13, 0.21	**<0.001*****	0.17 ± 0.02	0.13, 0.21	**<0.001*****				0.12 ± 0.02	0.09, 0.16	**<0.001*****	0.13 ± 0.02	0.09, 0.16	**<0.001*****
Perceived bird pleasantness × Perceived traffic volume				−0.02 ± 0.008	−0.04, 0.007	**0.002****							−0.02 ± 0.007	−0.04, −0.008	**0.002****
Perceived bird species							0.22 ± 0.05	0.11, 0.32	**<0.001*****	0.10 ± 0.05	0.003, 0.20	**0.044***			
Perceived naturalness							0.40 ± 0.05	0.38, 0.44	**<0.001*****	0.31 ± 0.02	0.27, 0.34	**<0.001*****	0.31 ± 0.02	0.28, 0.35	**<0.001*****
Noise sensitivity													0.21 ± 0.07	0.06, 0.35	**0.006****
Noise sensitivity × perceived traffic volume													−0.02 ± 0.01	−0.04, −0.003	**0.025***
	$R^2_m = 0.35$; $R^2_c = 0.63$			$R^2_m = 0.35$; $R^2_c = 0.63$			$R^2_m = 0.44$; $R^2_c = 0.67$			$R^2_m = 0.54$; $R^2_c = 0.73$			$R^2_m = 0.54$; $R^2_c = 0.73$; AIC = 3,749.68		

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 2 Summary of multiple regression models (regression coefficients, standard errors and *p* values) for the outcome variable perceived restorative outcomes scale (ROS)

Dependent variable: Perceived restorative outcomes scale (ROS)															
	Perception of soundscapes (Model 1)			Perception of soundscapes + moderators (Model 2)			Perception of env. characteristics (Model 3)			Perception of soundscapes + env. characteristics (Model 4)			Perception of soundscapes + env. characteristics + moderators (Model 5)		
	B ± *SE*	95% CI	*p*	*B* ± *SE*	95% CI	*p*	*B* ± *SE*	95% CI	*p*	*B* ± *SE*	95% CI	*p*	*B* ± *SE*	95% CI	*p*
Perceived bird volume	0.22 ± 0.02	0.16, 0.26	**<0.001*****	0.22 ± 0.02	0.19, 0.29	**<0.001*****				0.12 ± 0.02	0.07, 0.16	**<0.001*****	0.12 ± 0.02	0.08, 0.17	**<0.001*****
Perceived traffic volume	−0.10 ± 0.05	−0.29, −0.21	**<0.001*****	−0.10 ± 0.05	−0.20, −0.01	0.93				−0.15 ± 0.02	−0.19, −0.11	**<0.001*****	0.17 ± 0.06	0.05, 0.30	**0.006****
Perceived bird pleasantness	0.37 ± 0.04	0.22, 0.31	**<0.001*****	0.37 ± 0.04	0.26, 0.42	**<0.001*****				0.20 ± 0.02	0.16, 0.24	**<0.001*****	0.36 ± 0.04	0.27, 0.44	**<0.001*****
Perceived traffic pleasantness	0.15 ± 0.02	0.11, 0.19	**<0.001*****	0.15 ± 0.02	0.13, 0.21	**<0.001*****				0.12 ± 0.02	0.08, 0.15	**<0.001*****	0.13 ± 0.02	0.08, 0.15	**<0.001*****
Perceived bird pleasantness × perceived traffic volume				−0.03 ± 0.00	−0.04, 0.007	**0.002****							−0.03 ± 0.007	−0.04, −0.01	**<0.001*****
Perceived bird species							0.13 ± 0.05	0.02, 0.24	**0.018***	0.005 ± 0.05	−0.10, 0.10	0.92			
Perceived naturalness							0.38 ± 0.02	0.34, 0.41	**<0.001*****	0.26 ± 0.02	0.22, 0.30	**<0.001*****	0.25 ± 0.02	0.22, 0.29	**<0.001*****
Time lived in Brisbane													0.04 ± 0.02	0.002, 0.07	**0.038**
Time lived in Brisbane × Bird pleasantness													−0.006 ± 0.002	−0.04, −0.01	**0.018***
Noise sensitivity													0.36 ± 0.08	0.20, 0.51	**<0.001*****
Noise sensitivity × traffic volume													−0.04 ± 0.01	−0.06, −0.02	**0.025***
	$R^2_m = 0.35$; $R^2_c = 0.63$			$R^2_m = 0.35$; $R^2_c = 0.63$			$R^2_m = 0.35$; $R^2_c = 0.64$			$R^2_m = 0.54$; $R^2_c = 0.73$			$R^2_m = 0.54$; $R^2_c = 0.73$; AIC = 3,885.20		

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

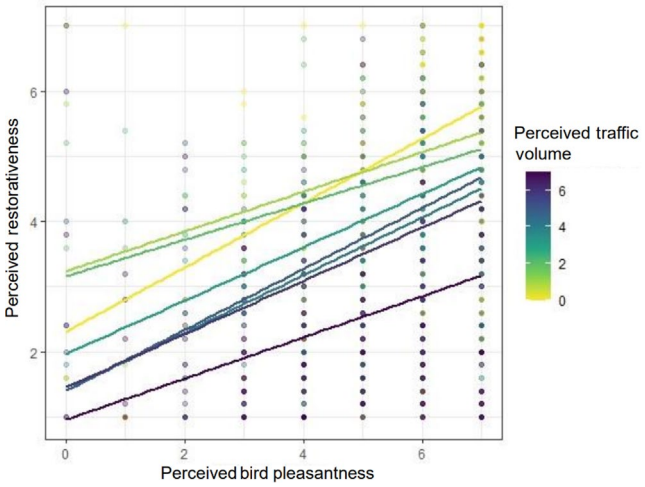


FIGURE 5 The association of perceived restorativeness of soundscapes (PRSS-SF) and perceived bird pleasantness as a function of perceived traffic volume for eight sound samples. All scores rated on a 7-point scale

naturalness ($p < 0.001$) were positively associated with higher perceived restorative outcomes scores but perceived bird species was not (Table 2).

The final model included all variables (perceptions of soundscapes, environmental characteristics and moderating items). With perceived restorativeness as the dependent variable, perceived bird pleasantness, perceived bird volume, perceived traffic pleasantness and perceived naturalness were significantly associated with higher perceived restorativeness scores. Perceived traffic volume remained as a significant moderator of the relationship between bird pleasantness and perceived restorativeness. Additionally, noise sensitivity ($p = 0.006$) displayed a negative interaction with perceived traffic volume ($p = 0.025$; Table 1), where people with stronger noise sensitivity exhibited stronger negative impacts of traffic volume on perceived restorativeness.

The same associations were found when the final model was repeated for perceived restorative outcomes, with several notable additions. Perceived traffic volume and the amount of time lived in Brisbane were also significantly associated with higher perceived restorative outcomes scores (Table 2). The amount of years lived in Brisbane, however, marginally reduced the effect of bird pleasantness on perceived restorative outcomes scores (Table 2).

4 | DISCUSSION

This study assessed the restorative potential of urban green space soundscapes with respect to perceptions of bird calls and the moderating impact of perceived traffic noise. Our results showed greater perceived restorative potential and outcomes for park soundscapes when birds were perceived as both louder and more pleasant; however, perceived traffic noise was found to diminish the potential restorative effects of perceived birds sounds. A number of other perceptions and participant characteristics were also found to be important influences on perceived restorativeness, including perceived naturalness, perceived bird species richness and personal attributes such as noise sensitivity. These results highlight the importance of considering the sonic environment when assessing the potential restorative benefits of an urban green space and managing the composition of natural and anthropogenic sounds within these green spaces.

Previous studies have demonstrated that urban park soundscapes can be restorative and that natural soundscapes are rated as more restorative than urban sonic environments (Krzywicka & Byrka, 2017; Payne, 2008, 2013). These results build on this previous research to demonstrate potential restorative gradients as park soundscapes are perceived as more natural, highlighting the importance of these subjective perceptions. This also supports the findings of Levenhagen et al. (2020), who found park visitors reported greater pleasantness of natural sounds when other human-made sounds were mitigated. Importantly, by assessing the combined effect of beneficial and non-beneficial sounds, we could demonstrate that increasing perceptions of traffic volume undermined the beneficial effects of bird pleasantness. Recently, Suko et al. (2019) found that faint levels of traffic noise among birdsongs resulted in significantly less physiological restoration than birdsongs without traffic noise. However, with respect to perceived restorativeness, the same study did not find any significant differences with or without the traffic noise amongst bird songs. Our results here demonstrate more strongly that increasing traffic noise impacts the perceived restorativeness of natural soundscapes. This is a notion supported by the constrained restoration concept (Hartig et al., 2007) which contends that restoration may become impaired by certain environmental conditions. In this context, the restorative experience of a soundscape consisting of bird sounds is diminished when traffic volume becomes an increasing feature of the overall soundscape. It is also important, however, to acknowledge the interplay between visual and auditory pathways. Studies have shown, for example, that bird songs are rated more positively when accompanied with congruent visual stimuli (Hedblom et al., 2014). Given this, the environmental conditions experienced in an urban park in situ involve several sensory pathways, including visual, potentially resulting in different results seen here.

Both pleasantness and volume of both bird and traffic sounds were important factors in restorative qualities and outcomes of the park soundscapes. Previous studies have demonstrated bird songs are largely rated positively (Hedblom et al., 2014; Krzywicka & Byrka, 2017) and, correspondingly, associated with greater restoration (Krzywicka & Byrka, 2017). While Ratcliffe et al. (2013, 2020) reported that loud bird sounds can be perceived as more threatening and less restorative, in our study the perceptions of bird call volume were associated with greater restoration. This may indicate that perceived bird volume was related to perceptions of more birds being present in the recording, that is, a higher abundance, rather than the loudness of birds per se, a notion supported by the high correlation of perceived bird awareness with perceived bird volume. Although limited research has focussed on perceptions of traffic volume, this aligns with previous findings highlighting the negative impact of unwanted sounds above certain objective levels (Berglund et al., 2000; WHO, 2011).

The perceived naturalness of the soundscape was also an important factor and strongly associated with perceived restorative qualities

and outcomes. This was similarly found by Carrus et al. (2013) in a visual context in which photos of parks that were rated more natural were associated with greater perceived restorativeness. Notably, parks samples rated the most natural also had the greatest objective and perceived bird species richness and the lowest objective and perceived traffic noise scores. While perceived bird species richness was associated with greater restorative potential and outcomes in some scenarios, it was not an important factor in complete model analyses, indicating that, overall, perceived naturalness was the more important variable. This may be a result of traffic sounds in recordings which may not unduly affect perceptions of bird species within the soundscape but, almost by definition, may impact perceptions of naturalness. Nevertheless, given that the natural sounds in recordings were almost exclusively bird calls, there is a strong implication that actual bird species richness is driving greater perceptions of naturalness within the recordings.

Participants who had lived in the city for longer and those sensitive to noise were also associated with increased perceived restorative outcomes while noise-sensitive people were also more negatively affected perceived traffic volume. Noise sensitivity appears to be partially genetic and is associated with a higher prevalence of hypertension and pronounced stress and anxiety (Heinonen-Guzejev et al., 2005; Ojala et al., 2019; Stansfeld, 1992). Natural soundscapes appear to be particularly important for this segment of the population, providing benefit from a quiet soundscape and an absence of annoyances such as traffic noise. Conversely, a soundscape containing high levels of traffic noise appears to be particularly problematic for noise-sensitive people. This aligns with a framing of noise-sensitive people as being sensitive to poor environmental quality (Ryu & Jeon, 2011). Although it is difficult to make robust generalisations, participants who had lived in the city for longer may exhibit a stronger sense of place attachment and connection to urban green spaces and common bird calls experienced from these nature interactions. Previous studies indicate that greater place identity is positively associated with well-being (Knez et al., 2018) while place attachment has been linked to a greater sensitivity of the environmental conditions of a place (Eder & Arnberger, 2012).

4.1 | Implications for practice

These results provide evidence that urban green space soundscapes with a greater array of perceived bird sounds and minimal perceived traffic noise can provide greater potential for restorative benefits to human health and well-being. In contrast, excessive perceptions of traffic noise can dampen these positive effects.

Urban planners and policymakers may maximise the restorative potential of urban green spaces by promoting greater diversity and abundance of birds within parks. Depending on the subset of bird species prevalent in the region, this may include strategic planting of vegetation, such as flowering and fruiting plants or trees, the inclusion of waterways, such as lakes or ponds, or providing an appropriate mix of open grassland with forested areas.

For existing parks in areas of dense traffic, noise mitigation and traffic reduction strategies should be a key focus. Factors known to influence traffic noise levels include the amount, type and speed of vehicles, along with the distance and type of surface between the source of noise and the receiver (i.e. the park; Rochat & Reiter, 2016). Accordingly, policies might consider traffic speed limits along streets adjacent to parks and restrict large trucks, which can be up to 10 times as loud as a regular vehicle (Rochat & Reiter, 2016). Where possible, acoustically soft surfaces in between parks and main roads, such as grass or loose dirt would attenuate more noise than smooth surfaces, such as concrete and asphalt. Natural features such as trees and bushes or man-made barriers that block sound can also be effective in impeding noise propagation (Rochat & Reiter, 2016). Policies that contribute towards traffic reduction, such as promoting greater use of bicycle lanes and public transport could also be effective. A long-term transition towards electric cars could also assist in traffic noise reduction.

Urban planners might also consider areas spatially within parks likely to contain the most natural soundscapes and promote use of these areas, particularly for people visiting to experience nature or tranquillity. This may, for example, involve increased provision of seating in areas of higher vegetation that are removed from park boundaries. Organised group nature walks could also explicitly consider green spaces with highly natural soundscapes in addition to the visual features of the park to increase perceptions of restorative qualities and maximise psychological and emotional well-being (Marselle et al., 2016).

Notably, the parks soundscapes included in our assessment resembled everyday encounters, such as those experienced by a morning park visit or during a commute to work. To gain from the beneficial effects of biodiversity in daily life and enhance the opportunity of achieving a substantial weekly nature dose through effortless contact, urban planners should seek to consider the design of green spaces in easily accessible places or known routes of commuters.

4.2 | Limitations and future directions

The park soundscape samples assessed were recorded at a single location on a path between 6.30 and 7.30 a.m. on week days in parks around Brisbane, Australia. Although this provided an example of a real-world soundscape sample commonly experienced by park visitors, soundscapes can vary significantly over space and time (Pijanowski et al., 2011). A useful future focus would be to further investigate temporal and spatial variability, particularly differences between morning and late afternoon soundscapes, as the psychological benefits of bird sounds may differ during the day (Cox et al., 2017). There may also be differences spatially within parks, particularly between park boundaries, which may be subject to higher levels of traffic noise compared to areas more towards the centre of parks. At a broader scale, there may also be differences depending on the geographical region and local avian community which could be further explored. Participants in this study were also a homogeneous group

who were all young University students between the ages of 18 and 30 years, potentially limiting our ability to make generalisations about the wider population. Future studies could seek to assess a more representative sample of the population that encompasses a broader socio-demographic spectrum, including older adults and people with hearing loss (Van Kamp & Davies, 2013).

Future research could further examine how perceived restorativeness might differ between particular bird species. Previous studies have indicated that not all bird calls are perceived favourably, with some bird calls viewed as threatening or aggressive associated with negative appraisals and higher arousal (Ratcliffe et al., 2013). Another line of research might explore the potential of priming a park visitor to sounds of nature through information signs at park entrances or by other means (Colléony et al., 2020; Duvall, 2011). This may assist in generating greater awareness of bird sounds, a factor associated with greater perceived restorativeness and perceived restorative outcomes in this study. In particular, strategies could focus on highlighting bird species known for their melodic, pleasant calls, such as songbirds (Cox & Gaston, 2015). The amount of time lived in Brisbane, while potentially indicative of greater familiarity or place attachment with local parks and birds, does not allow for robust generalisations about these two factors. Direct assessments about familiarity and place attachment would also be useful inclusions in future research.

This study also had a specific focus on the auditory pathway and, as such, we deliberately provided no accompanying visual stimuli of parks, so as not to confound analyses. Although there have been relatively few studies with a focus exclusively on the restorative effects of soundscapes (Ratcliffe, 2021), studies also show an important interplay between visual and auditory perceptions of nature (Hedblom et al., 2014, 2019; Zhao et al., 2018) and this constitutes an important area of future focus.

4.3 | Conclusions

There is growing recognition that the provision of urban green spaces allows for benefits to human health as well as the conservation of biodiversity. Soundscapes are an important means through which humans perceive nature and warrant careful consideration in the management of green spaces. In conjunction with visual features, the sonic environment can further enhance perceptions of nature and highly natural soundscapes can help facilitate synergistic human–nature outcomes. Importantly, results also indicated that park soundscapes associated with the highest potential for perceived restorativeness were from parks with the highest actual bird species richness, further highlighting the potential ecological, as well as psychological, benefits of promoting higher biodiversity in parks. Conversely, when offset by heavy traffic noise the benefits of soundscapes in green spaces can be confounded and limited. Therefore, urban nature-based solutions should seek to (a) include opportunities to experience urban greenspaces and natural soundscapes into everyday life, for example, when commuting to work on foot or bicycle through parks or green cycle lanes and to (b) minimise traffic and other anthropogenic noise in otherwise natural soundscapes.

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CONFLICT OF INTEREST

Aletta Bonn and Melissa Marselle are Associate-Editors of *People and Nature*, but took no part in the peer review and decision-making processes for this paper.

AUTHORS' CONTRIBUTIONS

K.U., M.M., A.J.D., J.R.R. and A.B. conceived the ideas and designed the methods; K.U. collected the data; K.U. analysed the data and led the writing of the manuscript. All the authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The survey data used for this study are available at UQ eSpace https://doi.org/10.14264/b1a04ed (Uebel, 2021).

ORCID



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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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Assessment of the psychopathological effects of a horticultural therapy program in patients with schizophrenia

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Highlights

- A horticultural therapy program improved the scores of schizophrenic patients in the Positive and Negative Syndrome Scale.
- A horticultural therapy program improved clinical symptoms in the Brief Psychiatric Rating Scale of schizophrenic patients.
- A horticultural therapy program significantly improved psychopathological symptoms of patients with schizophrenia.
- This study showed the potential of horticultural therapy for improving psychopathologic symptoms of psychiatric patients.

Article preview

Abstract

Introduction

Section snippets

References (56)

Abstract

Objectives

This study assessed the psychopathological effects of participation in a 10-session horticultural therapy program in patients with schizophrenia.

Design

[redacted]

The study design was pre and post test design of experimental and control groups.

Setting

Twenty-eight Korean patients with schizophrenia, recruited from a mental health clinic and two mental health rehabilitation centers in Suwon, South Korea, were voluntarily assigned to either a control group (average age: 33.4±9.4years) or a horticultural therapy group (average age: 42.1±13.0years).

Interventions

The participants in the horticultural therapy group participated in a 10-session horticultural therapy program designed around various plant cultivating activities. The horticultural therapy program involved sessions once a week from April 2017 to June 2017.

Main outcome measures

A psychiatrist evaluated the psychopathological symptoms of schizophrenic patients in both groups. To assess the clinical psychopathological effects, the Korean version of the Positive and Negative Syndrome Scale (PANSS) and Brief Psychiatric Rating Scale (BPRS) were used.

Results

The horticultural therapy group significantly improved in terms of positive, negative, and general symptoms on the PANSS after the 10-session horticultural therapy program. Moreover, the horticultural therapy group significantly improved in terms of clinical symptoms of schizophrenia in BPRS after the 10-session horticultural therapy program. However, there was no change in the PANSS and BPRS scores in the control group.

Conclusions

This study showed the potential of horticultural therapy in improving psychopathological symptoms in psychiatric patients. Future studies should investigate the effects of long-term horticultural therapy program on the chronic symptoms of patients with schizophrenia.

Keywords

Complementary and alternative medicine; Consumer horticulture; Gardening; Mental illness; Socio horticulture

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Introduction

Schizophrenia is a severe psychiatric disorder that leads to chronic symptoms.1, 2. The positive and negative symptoms of schizophrenic patients induce thinking disorder, blunted affect, attention or memory problems, due to distortion of reality.[3] Consequently, patients with schizophrenia lack coping skills, and have social and occupational functioning failings,[4] resulting in a low level of quality of life.[5]

Although pharmacological treatment has been used to stabilize mental disease symptoms, a combination of pharmacological and non-pharmacological treatments are considered more effective for the treatment of the chronic symptoms of schizophrenia.[6] It is important that patients with schizophrenia adapt to the community and that relapse is prevented; therefore, various rehabilitation training programs, such as horticultural therapy, music therapy, dance therapy, art therapy, physical therapy have been applied to improve daily living abilities and social skills.7, 8

The therapeutic use of horticulture has been documented as far back as ancient Egypt, when court physicians instructed royalty to walk among the palace gardens as a prescription for mental illness.[9] The use of horticulture gradually came to be recognized as an acceptable form of therapy for use in mental health institutions by the late 1700s and early 1800s, in the United States and Europe10, 11, 12 and by the 1980s, in South Korea.[13]

Horticultural therapy is defined as a complementary and alternative treatment that is provided by trained professionals, and involves horticultural activities in a pre-designed intervention with therapeutic goals and objectives for improving or recovering health. A recent review article about horticultural activity interventions reported that most previous related studies focused on the psychological or emotional effects of horticultural intervention.[14] In particular, this horticultural intervention led to improved self-esteem and emotional intelligence, and reduced stress and depression.[15]

A previous study reported that a 16-session horticultural therapy program improved self-efficacy and reduced psychiatric symptoms in patients with schizophrenia.[16] Cho et al.[17] reported that a 24-session horticultural therapy program improved psychopathological symptom, assertiveness, and interpersonal relationships in patients with schizophrenia. Song and Sim[18] also showed a significant improvement in psychopathologic symptoms of patients with schizophrenia after a 10-session horticultural therapy program. Parvin

et al.[19] showed that a 3-month horticultural therapy program significantly improved both positive and negative symptoms in these patients.

However, few studies have assessed the psychopathological effects of a horticultural therapy program on patients with schizophrenia. Therefore, the objective of this study was to assess the psychopathological effects of participation in a 10-session horticultural therapy program, designed around plant cultivating activities, in patients with schizophrenia.

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Section snippets

Research subjects

A total of 28 Korean patients with schizophrenia participated in this study. To recruit patients with schizophrenia, a flyer containing the information about the study objective, horticultural therapy program, and health measures was distributed at a mental health clinic and two mental health rehabilitation centers in Suwon, South Korea. A consent form for each patient was obtained from the patients and a person in charge of the facilities before starting the study. All of the participants were …

Positive and negative syndrome scale (PANSS)

The schizophrenic patients in the horticultural therapy group significantly improved in terms of positive, negative, and general symptoms after the 10-session horticultural therapy program (Table 3). On the other hand, there was no change in the positive, negative,

or general symptoms of the PANSS in the control group. There was no difference between the groups for the pre-values of PANSS (data not shown).

Although the effects of a horticultural therapy program on patients with schizophrenia …

Acknowledgements

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Journal of PHYSIOLOGICAL ANTHROPOLOGY

ORIGINAL ARTICLE Open Access

Psychological and physiological effect in humans of touching plant foliage - using the semantic differential method and cerebral activity as indicators

Abstract

Background: Numerous studies have reported on the healing powers of plants and nature, but there have not been so many instances of experimental research. In particular, there are very few psychological and physiological studies using tactile stimuli. This study examines the psychological and physiological effects of touching plant foliage by using an evaluation profile of the subjects' impressions and investigating cerebral blood flow.

Methods: The subjects were 14 young Japanese men aged from 21 to 27 years (mean ± standard deviation: 23.6 ± 2.4). With their eyes closed, the subjects touched four different tactile samples including a leaf of natural pothos (*Epipremnum aureum*). The physiological indices were compared before and after each stimulus. Psychological indices were obtained using a 'semantic differential' method.

Results: The fabric stimulus gave people 'soft' and 'rough' impressions, 'kind', 'peaceful' and 'pleasant' feelings psychologically, and a sense of physiological calm. On the other hand, the metal stimulus gave people 'cold', 'smooth' and 'hard' impressions and an image of something 'artificial'. The metal stimulus caused a stress response in human cerebral blood flow although its evaluation in terms of 'pleasant or unpleasant' was neutral. There were no remarkable differences between the stimuli of natural and artificial pothos compared with other types of stimulus psychologically. However, only the natural pothos stimulus showed a sense of physiological calm in the same appearance as the fabric stimulus.

Conclusions: This study shows that people experience an unconscious calming reaction to touching a plant. It is to be concluded that plants are an indispensable element of the human environment.

Keywords: Cerebral blood flow, Complementary and alternative medicine, Nature, NIRS, Plant foliage, Pothos, Semantic differential method, Sense of touch, Tactile, Therapy

Background

The artificial environments in which modern human beings live have produced many kinds of stress. In particular, unfavorable economic conditions in recent years have resulted in increased mental stress. As a result, the world has been flooded with various therapies. These therapies are not only used for relaxation or release from tension in daily life, but also as complementary and alternative medicine (CAM) to the medical treatment of and rehabilitation from illness and physical and mental handicaps [1]. There are several reasons why CAM has been the focus of increasing attention in modern society, including the limitations of Western medicine in treating chronic diseases and stress-related disorders, rising medical expenses caused by low birth rate and longevity, and increased levels of patient interest in the selection of medical treatment [1]. However, there is little significant evidence for CAM. Significantly more medical and scientific evidence is required in order for CAM to be better utilized to improve quality of life and activities of daily living.

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Many types of CAM bear some relation to plants. According to Imanishi [1], a search of MEDLINE with the keyword 'CAM' in 2007, indicated that 41% of CAM was 'phytotherapy', while 15% of CAM could be termed 'medicine-traditional', a form of medicine that uses pharmaceuticals and oils made from plants, such as kampo (Chinese traditional) medicine and Ayurveda. This suggests that plants are indispensable in healing.

Recently there has been an accumulation of medical and scientific evidence in this discipline [2]. However, the healing mechanisms of plants or natural environments are not clear, because people and plants are both complex systems. The different dimensional effectiveness of plants and nature has not been clarified and this remains a barrier to clearly understanding their healing mechanisms. In any case, as a minimum indicator of their healing mechanisms, it is important to show the psychological and physiological effects of plants and nature. Many studies on the therapeutic power of plants and natural environments have been conducted [3-5]. These studies show the restorative effect and reduction in stress levels that come about through nature, regardless of their varied theoretical backgrounds [6]. One recent study reports that positive affect increased and anger decreased after 50 minutes of walking in a nature reserve; the opposite pattern emerged in an urban environment [3]. Forest environments in particular have been the focus of 'forest therapy' or 'forest bathing' in Japan. Many studies of forest therapy have been conducted. These studies report that various elements of forest environments cause people to relax physiologically and psychologically [7-9]. Recently, the influence of nature therapy has been the subject of much attention from an epidemiological viewpoint and studies show a link between green spaces and the rate of disease [10].

Horticultural therapy is one of the most popular therapies utilizing the healing power of plants. Horticultural therapy was originally developed for the mental health care of returned soldiers in the United States. Nowadays, horticultural therapy has been used with various target groups, including psychiatric patients [11], dementia patients [12], older people [13], children [14], and prisoners [15]. The many reports conducted show the mental, physical, and social effects of horticulture therapy. However, most of these reports come from anecdotal evidence collected in various settings. A clear causal relationship between people and plants has not been discussed, since many complicated factors are involved [16].

More experimental research is necessary to clarify the healing mechanism of plants. How do people detect stimuli using all five senses? How do plants influence peoples' minds and bodies? The majority of studies on the effect of stimuli concentrate on the visual sense [17-19]. Ulrich [18] examined the recovery rates of patients who underwent gall bladder surgery and found that those patients who had a natural scene to view recovered faster than those patients who viewed an urban scene. Kaplan showed that a view of nature from the window contributed greatly to the residents' wellbeing [17]. Moreover, there has been a gradual accumulation of experimental studies of the way in which the visual stimulus of nature and plants is reflected in the human mind and body [20,21].

There has also been a gradual increase in the number of studies of the effects of odor, such as the use of aromatherapy, and these studies shed light on the pharmacological and physiological effects of essential oils used experientially [22,23]. There have been more sophisticated studies of the effects of lavender, which is very well known as a traditional holistic relaxant. These studies reported an increase in parasympathetic modulation in middle-aged women with insomnia [24], the relaxing effect of lavender on patients undergoing cosmetic procedures [25], and a significant improvement of agitated behavior in severe dementia patients [26].

However, there are not so many studies regarding the other senses. The tactile sense has been especially neglected, in spite of its importance in human emotion.

Although the skin is the only sense organ that recognizes the real world [27], few studies deal with the tactile (the sense of touch). The skin's development originates in the same way as the brain and that is why it is sometimes referred to as 'the third brain' [28]. The skin is an organ that possesses higher functions, such as cognition and judgment [28].

Moreover, it is said that there is a close relationship between tactile stimuli and brain chemistry, such as oxytocin and serotonin [28,29], which manages the sociality of human beings. The latest research also shows strong relationship between touch and emotions [30].

Above all, the skin separates and distinguishes between human beings and the environment. The mind was not born without existence of the skin [31].

Previous studies on the tactile sense and plants are limited. Abe and Masuyama [32] focused on the tactile qualities of wood as a material. Yamada [33] investigated the qualities of residence, and wood has excellent qualities for fit habitation. Miyazaki *et al.* [34] and Miyazaki and Morikawa [35] reported that touching wood gives one a relaxed feeling while touching metal induces a stress reaction. In this way, some previous studies dealt with the tactile nature of wood as a material, but only a few studies focused on empirical evidence that touching living plants gives people a feeling of comfort and relaxation [36,37].

Animal-assisted therapy is known as a therapy that utilizes living creatures. Plant-assisted therapies, such as horticultural therapy, are very similar to animal-assisted

therapies in that a social effect is expected through prolonged activity. On the other hand, the effect of short-term tactile stimuli of animal-assisted therapy is acknowledged [38,39], but the effect of short-term touching of plants is not.

Therefore, the aim of this study is to clarify the psychological and physiological effect of touching living plants in the laboratory. Since many previous studies show that plants and nature can have both recuperative and relaxing effects, it is to be expected that touching plants can also have psychological and physiological effects. Although the physiological mechanism of such theories advocated by Ulrich and Kaplan and Kaplan is not fully clear, it seems that there may be a positive influence on the immunological system as a result of lessening strain in the sympathetic nerve. In some past studies, Miyazaki has mentioned that activity in the prefrontal area was calmed by the olfactory stimulus of wood and the forest environment [40]. Therefore, the same change would be anticipated in this study through the stimulus of touching plant foliage. This understanding will help the fundamental understanding of the relationship between people and plants and contribute to the optimum uses of plants and green spaces in urban areas.

Methods

Subjects and stimuli

The subjects were 14 young Japanese men aged from 21 to 27 (mean ± standard deviation: 23.6 ± 2.4). The subjects gave informed consent to the experiment in accordance with the protocol reviewed and approved by the Human Investigation Committee of Chiba University.

Four different tactile experimental samples were prepared: a plate of aluminum, a piece of velveteen, a leaf of natural pothos (*Epipremnum aureum*), and a leaf of artificial pothos made of resin. Each material was held between two pieces of 10cm × 10cm square paper that had a 5cm square window cut out in front to make a planar sample (Figure 1). The sample of natural pothos was checked for quality after every session, and changed for a fresh leaf if it had been scratched or had noticeably dried.

Data collection

Subjects were seated on a chair while closing their eyes and putting their right hand on a table in front of them (Figure 2). The subjects rested their wrist only on the table with their fingers held lightly in the air above the table. They were then instructed to touch the sample with their fingers. The measuring devices were placed behind the subjects.

Physiological data were acquired, showing a concentrated change in cerebral blood flow (CBF) as an index of central nervous system activity. Cerebral function can be evaluated by measuring the activity of a nerve cell directly or by measuring the change in CBF accompanying nerve activity [41]. In recent years, optical topography using near infrared spectroscopy (NIRS) has attracted much attention from the point of view of time resolution, spatial resolution, and above all, from the point of view of the ease of measurement. Although NIRS was initially developed for diagnosing brain ischemia and low oxygen, it turns out that a change in CBF and oxygen metabolism accompanying nerve activity can be measured as a secondary signal, and that these signals can be applied to various fields as a method of cerebral

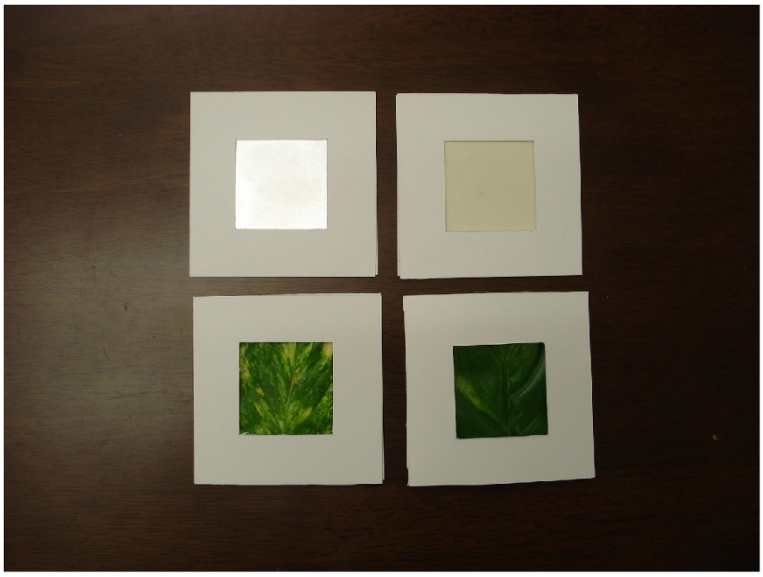


Figure 1 Tactile samples. The samples are, clockwise from top left, metal, fabric, artificial pothos, natural pothos.

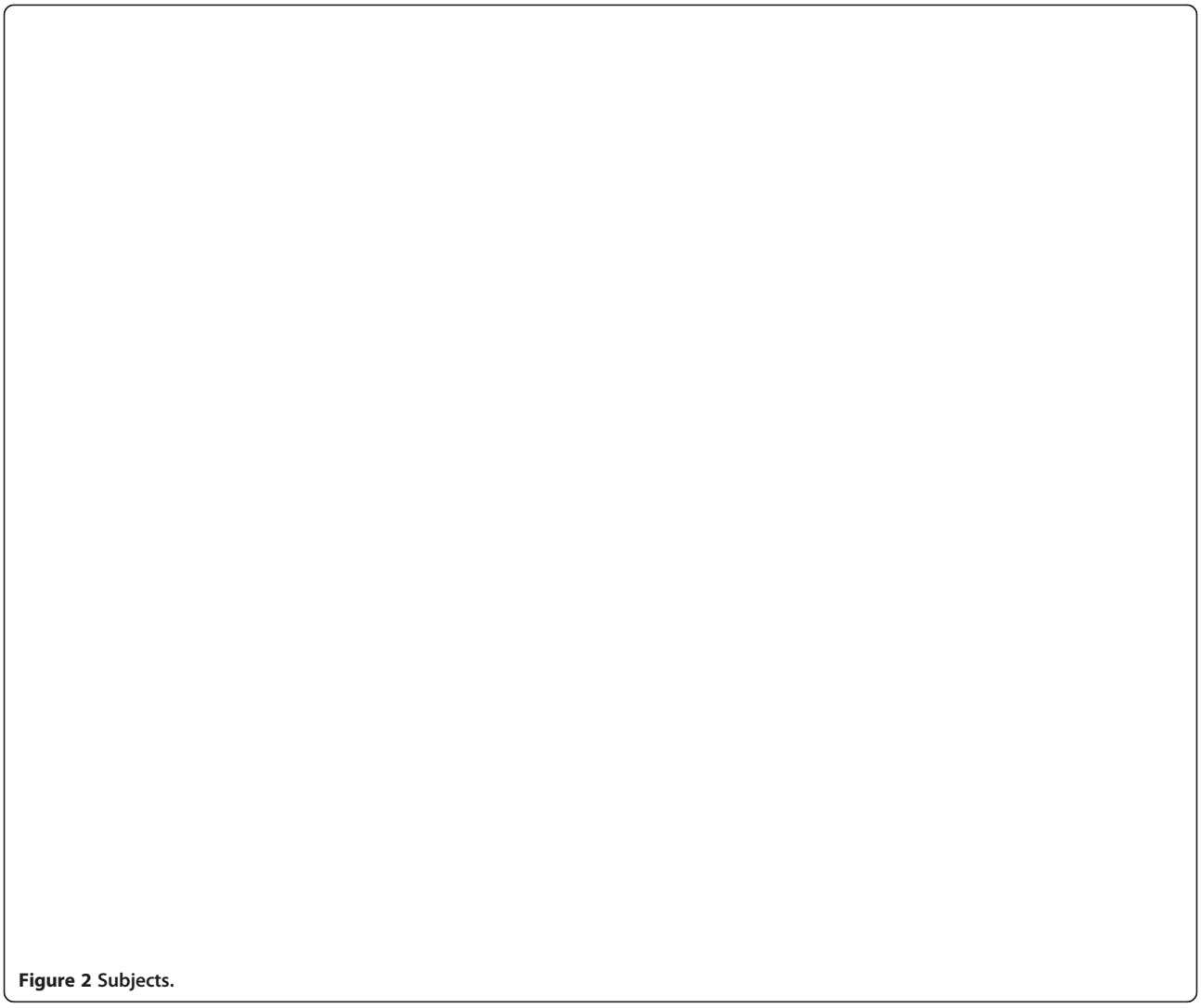


Figure 2 Subjects.

function imaging [42]. Although there is some disagreement about the extent of correspondence between nerve activity and substance movement, a similar nerve phenomenon is shown in previous research, which carried out simultaneous recording of electric activity and fMRI in the visual cortex of an ape [43]. The CBF was surveyed using near infrared spectroscopy by attaching two channel sensors on the right and left sides of the forehead (NIRS; NIRO-300; Hamamatsu Photonics, JAPAN). These locations in the brain play a critical role in higher cognitive functions, concentration, and emotion [44,45].

Psychological data were acquired using a semantic differential (SD) method to evaluate the profile of the subjects' impressions, and ten pairs of adjectives were used for SD (Table 1).

After the subject rested on a chair, CBF was recorded as 'pre-stimulus' for 30 seconds. Then according to the instructions, the subject touched the sample, after which the CBF was recorded as 'post-stimulus' for 120 seconds.

Table 1 Pairs of adjectives used in semantic differential method

Pairs of adjectives in English	Pairs of adjectives in Japanese
warm, cold	あたたかい–つめたい
smooth, rough	つるつる–ざらざら
soft, hard	やわらかい–かたい
natural, artificial	自然な–人工的な
familiar, unfamiliar	親しみやすい–親しみにくい
kind, unkind	やさしい–やさしくない
calming, stimulating	沈静的な–覚醒的な
peaceful, anxious	安心な–不安な
pleasant, unpleasant	快適な–不快な
like, dislike	好きな–嫌いな

The semantic differential was investigated after touching the sample. The subjects closed their eyes while conducting this experiment, but not while answering the SD questions. In this experiment, metal was used as the control and the samples were presented at random. Figure 3 shows the experimental protocol for this study. The experiment was carried out in the shielded room at Chiba University from 15 to 20 December 2010. The average temperature, the average humidity, and the average illumination factor were 21.2 ± 1.8°C (mean ± standard deviation), 54.7 ± 4.7% and 1050.0 ± 89.7 lux, respectively.

Data analysis

The CBF was recorded every one second and analyzed as oxygenated hemoglobin. Based on the contact time (t_0 = 0 seconds), data from −30 seconds to 0 seconds were averaged and used as the pre-stimulus. The difference between each post-stimulus and its corresponding pre-stimulus was analyzed by Student's t test paired comparison. Steel-Dwass's multiple comparison test was applied after one-way analysis of variance (ANOVA) for the comparison of SD scoring.

Results

Impression profiling evaluation

In the results of the SD method, the fabric was significantly warmer, rougher, softer, and more peaceful than the metal, the natural pothos, and the artificial pothos. The metal was significantly colder than the artificial pothos ($P < 0.01$; Figure 4, Table 2). Also, the fabric was significantly warmer than the metal ($P < 0.01$), the natural pothos ($P < 0.05$), and the artificial pothos ($P < 0.01$). The metal was significantly smoother and harder than the natural and the artificial pothos. In the 'natural or artificial' item, the metal was significantly more artificial than the fabric, the natural pothos, and the artificial pothos ($P < 0.01$). With regards to the 'kind or unkind' descriptor, the 'peaceful or anxious' descriptor, and the 'pleasant or unpleasant' descriptor, the fabric was significantly more 'kind', more 'peaceful', and more 'pleasant' than the metal, the natural pothos, and the artificial pothos ($P < 0.01$). Also, the fabric was significantly more 'like' than the metal and the natural pothos in the 'like or dislike' descriptor ($P < 0.05$).

The metal was considered to be significantly colder than the other materials as opposed to the fabric, which was regarded as significantly warmer than the other materials. Similarly, the smooth surface of the metal was seen as significant compared with the rough surface of the fabric. With regard to the adjectival descriptors of soft and hard, the hardness of the metal was considered significant. On the contrary, the fabric was considered to be significantly softer than the artificial pothos, but not the natural pothos. There was a significant positive tendency shown in the adjectival descriptors for the fabric; 'kind or unkind', 'peaceful or anxious', 'pleasant or unpleasant', and 'like or dislike', however there was no significant difference in the others. No difference between artificial and natural pothos was seen in any of the adjectival descriptors.

The SD results indicate that the differences between the metal and the fabric were clearly recognized, but not the differences between the natural pothos and the artificial pothos. In addition, people tended to have a feeling of comfort from contact with a softer and warmer material.

Cerebral hemodynamics

Figure 5 shows the time-series variations of CBF. As shown, the CBF of both frontal areas for the metal sample increase compared with the pre-stimulus results from 10 s to 20 s. Also, significant decreases of both prefrontal areas are continuously seen from 15 s to 75 s for the fabric sample. Moreover, the natural pothos sample showed significant decreases in the left prefrontal area around 70 s and in the right prefrontal area around 30 s. However, there was no significant difference in the stimulus of artificial pothos.

Discussion

Some previous studies have shown that pleasant feelings from tactile stimuli mainly originate in the surface roughness of materials, whether the touch is active or passive. We know from our daily experiences that smooth and soft textures like velvet produce pleasant feelings, and rough and hard textures produce unpleasant feelings [46-49]. In this experiment, it was recognized that fabric stimulus created 'soft' and 'kind' impressions in the subjects as well as the feeling of being 'comfortable', as past studies have shown. Metal produced a neutral rating in the 'pleasant or

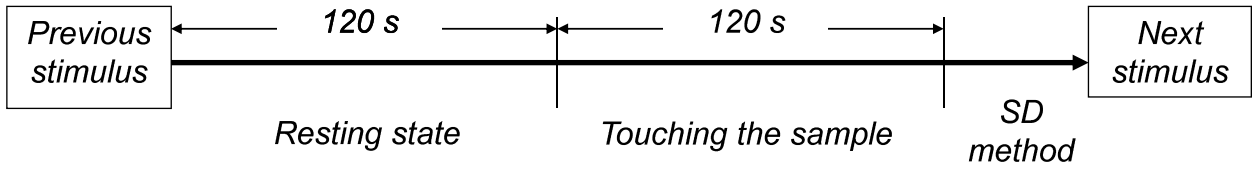


Figure 3 Experimental protocol.

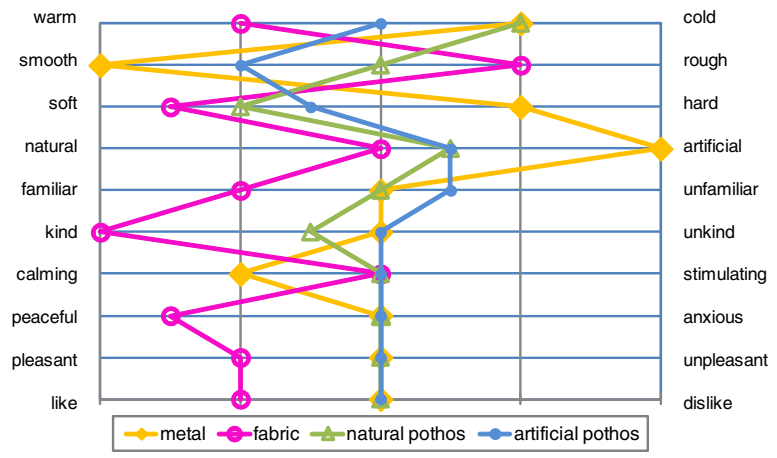


Figure 4 Result of the evaluation profile of the subjects' impressions using the SD method. These plots show median SD score.

unpleasant' descriptor, although it created a 'hard' impression, which induces relatively unpleasant emotions.

However, CBF in the orbitofrontal cortex (OFC) as a physiological index of 'pleasantness or unpleasantness' shows significant decrease in the fabric stimulus and significant increase in the metal stimulus.

There is currently some debate about the functional role of the prefrontal area with regards to tactile stimuli: Rolls [50] reported that there are different domains in the OFC, which work for pleasantness and unpleasantness, respectively; Hagen [51] detected the activity of neutral feeling valence in the OFC; and Kostopoulos [52] suggested that working memory was activated in the ventrolateral prefrontal cortex. Therefore, it is difficult to specify exactly what activity is taking place in the prefrontal area, because of the limitations of the NIRS, which has only two points of measurement. It has been proposed that the affective reaction caused by tactile stimuli is also found in domains other than the orbital prefrontal area [53]. However, it can be said that people showed a calming response physiologically to pleasant stimuli. This is shown in the physiologically significant reduction of oxygenated hemoglobin for the fabric stimulus in this experiment. On the contrary, a significant increase of oxygenated hemoglobin for the metal stimulus means that people feel physiological stress, although the results were neutral psychologically for the metal stimulus. The cause of this physiological stress is considered to be the cold stimulus when metal is touched. This was controlled in the laboratory, in order to eliminate the influence of differences in temperature of the materials. However, it is known that the warm-cold sense in touch is related to the conduction of heat between the skin and the materials touched [54]. The thermal conductivity of aluminum, used as the metal material in this experiment, is 236 W/mK [55], and is remarkably higher than that of fabric (0.16~0.32 W/mK) [56] or resin (0.08~0.42 W/mK) [57], and it may be considered that this caused the 'cold' impression, which is not evident in other materials.

Table 2 Summary of Steel-Dwass's test results using the subjective SD method

Adjectives	m-f	m-n	m-a	f-n	f-a	n-a
warm, cold	m < f**		m < a**	f > n**	f > a**	–
smooth, rough	m > f**	m > n**	m > a**	f < n*	f < a**	–
soft, hard	m < f**	m < n**	m < a**		f > a**	–
natural, artificial	m < f**	m < n**	m < a**	–	–	
familiar, unfamiliar	–		–	–	–	–
kind, unkind	m < f**	–		f > n**	f > a**	–
calming, stimulating	–	–	–			
peaceful, anxious	m < f**			f > n**	f > a**	
pleasant, unpleasant	m < f**			f > n**	f > a**	
like, dislike	m < f**			f > n**	f > a*	

*, $P < 0.05$ by Steel-Dwass's test; **, $P < 0.01$ by Steel-Dwass's test; -, any difference of median without statistical significance; >, the left side is larger than the right side in the descriptor; < the right side is larger than the left side in the descriptor. m, metal; f, fabric; n, natural pothos; a, artificial pothos.

Furthermore, the results from the natural pothos stimulus can also be discussed based on these findings. There was a slight, although statistically significant reduction in CBF, despite an unclear impression psychologically.

LeDoux [58] suggested a model of two pathways, which indicates that there are two amygdale pathways for arising affects; one is 'low road', from thalamus to amygdale directly, and the other is 'high road', from thalamus to amygdale via cortex. It is considered that the affect through the 'high road' would be conscious as subjective experiences, but the affect through the 'low road' would be expressed as physiological effects without recognition in this hypothesis. We could insist the existence of 'low road', when the

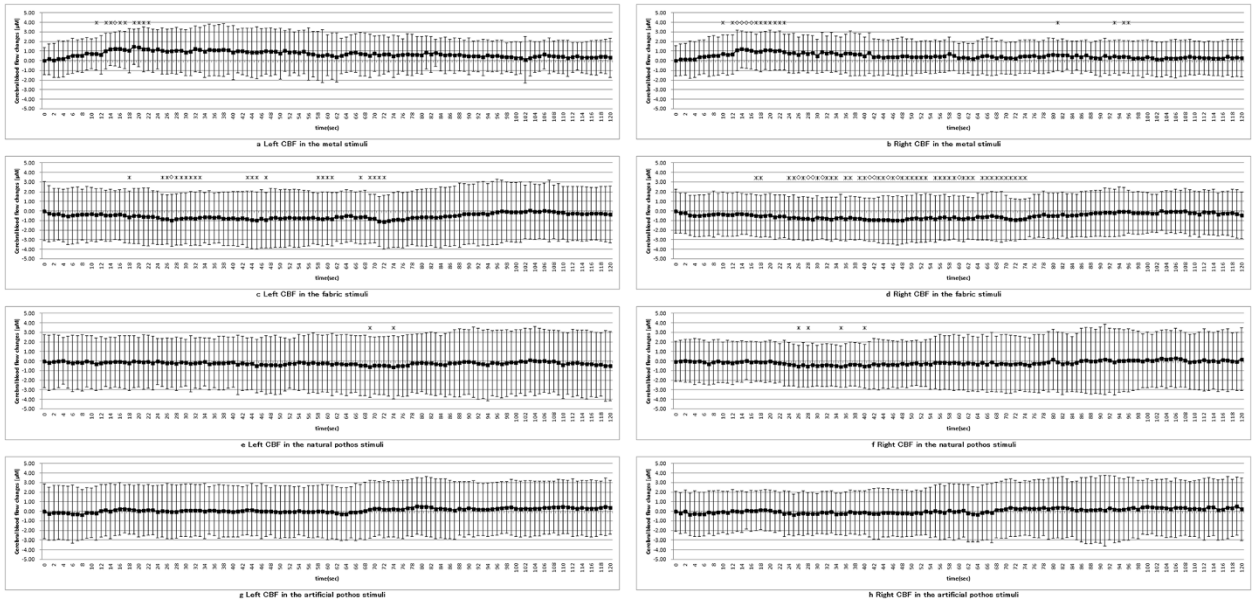


Figure 5 Time-series variations in cerebral blood flow. * $P < 0.05$ by Student's *t* test compared with pre-stimulus (average for 30 s) ◇ $P < 0.01$ by Student's *t* test compared with pre-stimulus (average for 30 s). CBF rose significantly immediately after touching the metal (**a, b**). Significant decreases in CBF were continuously seen between 10 s and 80 s with the fabric (**c, d**). For the natural pothos stimulus, there was a slight but significant reduction in CBF in the first half of the stimulus for the right frontal lobe and in the latter half of the stimulus (**e, f**) for the left frontal lobe. However, there was no significant difference in the stimulus of artificial pothos (**g, h**).

directions of psychological and physiological reaction are different, or the stimulus cannot be recognized clearly. The natural pothos stimulus made a slight, although significant reduction in the amount of CBF, despite having left a weaker impression than the fabric and the metal psychologically and indicating neutral in the descriptor of 'pleasant or unpleasant' in our experiment. This could imply the existence of the affect arising through 'low road', or unconscious physiological reaction to the touch of a natural pothos. It is thought that the touch of a natural pothos cause an unconscious physiological calming reaction. This supports the results shown in the tactile experiments with wood of Miyazaki *et al.* [59] and Morikawa *et al.* [60].

Most studies of affective touch have been conducted by a psychophysical approach and the evaluation of impressions of 'pleasantness or unpleasantness' is made by verbal methodology while the subject is conscious. However, at present, it is generally agreed that cognition of the stimulus that causes emotions is not necessary for the emotions to occur [61]. That is to say, the findings in this experiment show that emotions also arise while unconscious. It seems that as a result of processing tactile stimuli of a leaf of natural pothos, people were made to produce physiological calmness from an unconscious state. The psychological index and the physiological index did not coincide in the previous study [60], and it has been shown that the physical reaction and the cognition of 'pleasant or unpleasant' emotions did not necessarily correspond.

According to the triune brain hypothesis proposed by MacLean [62], the brain has peculiar functions, which can be divided into three: a reptile's brain (hypothalamus, and so on), the old mammal's brain (limbic system), and a new mammal's brain (cerebral neocortex). These peculiar functions depend on the evolutional stage and these three brains have a hierarchy [62]. Based on this concept of the hierarchy of the brain, if it is because of the information processing that determines how creatures adapt to their environment that pleasant or unpleasant emotions arise in a primitive reptile's brain [63], then it is possible that the physiological reaction that arises from touching a leaf of the natural pothos may be an essential message from the primitive brain that plants are indispensable to the living environment of human beings.

Conclusions

It was found that actively touching a leaf of natural pothos caused people to experience an unconscious calming response. This research supports the various previous studies that plants, nature, and material of natural origin bring feelings of relaxation to people. The results of this experiment might have been different if leaves with various different surface types had been used and it is necessary to examine this further. This report offers a new

framework for understanding the relationship between human beings and plants or nature.

Consent

Written informed consent was obtained from the subject for publication of this report and any accompanying images.

Abbreviations

ANOVA: Analysis of variance; CAM: Complementary and alternative medicine; CBF: Cerebral blood flow; ERP: Event-related potentials; NIRS: Near infrared spectroscopy; OFC: Orbitofrontal cortex; SD: Semantic differential.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

KK designed and carried out the study, performed the statistical analysis and drafted the manuscript. Administrative supervision was provided by IY. Both authors read and approved the final manuscript.

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ORIGINAL ARTICLE

Physiological effects of touching hinoki cypress (*Chamaecyparis obtusa*)

[redacted]

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Abstract

This study aimed to clarify the physiological effects of touching hinoki cypress (hereinafter called "hinoki") (*Chamaecyparis obtusa*) wood with the palm of the right hand on brain activity and autonomic nervous activity. Twenty-two female university students (mean age 21.1 ± 0.2 years) participated in the study. As an indicator of brain activity, oxyhemoglobin (oxy-Hb) concentrations were measured in the left/right prefrontal cortex using near-infrared time-resolved spectroscopy. Heart rate variability (HRV) was used as an indicator of autonomic nervous activity. The high-frequency (HF) component of HRV, which reflected parasympathetic nervous activity, and the low-frequency (LF)/HF ratio, which reflected sympathetic nervous activity, were measured. Plate (300 × 300 mm) of uncoated hinoki was used as tactile stimulation. Marble was used as a control material. After sitting at rest with their eyes closed, the participants touched the materials for 90 s with their eyes still closed. The results showed that tactile stimulation with hinoki significantly decreased oxy-Hb concentration in the left prefrontal cortex and increased ln(HF) reflected parasympathetic nervous activity compared with marble. In conclusion, our study showed that touching hinoki wood with the palm calms prefrontal cortex activity and increases parasympathetic nervous activity, thereby inducing physiological relaxation.

Keywords Japanese cypress · Tactile · Autonomic nervous activity · Prefrontal cortex activity · Physiological relaxation

Introduction

The stress that modern society brings on humans, especially "technostress [1]," is known to cause an increase in stress conditions [2]. In 2008, it was reported that more than 3.3 billion people—half of the globe's population—lived in an urban environment [3]. Lederbogen et al. [4] showed that social stressors increased the amygdala activity of the brain more in urban residents than in rural residents. Therefore, urban residents react excessively to stress. Because of the stressful conditions of modern society, the effects of exposure to natural stimuli on relaxation are receiving increasing attention [5].

Wood is a familiar, natural material that is used in houses and furniture, and it is empirically known to have a relaxing effect on humans [6]. A review outlining the current state of research regarding the physiological effects of wood-derived stimulation on humans [6] reported that data on the physiological effects of olfactory stimulation have continued to accumulate, following the development of physiological measurement technology in recent years. The oldest report, published in 1992, focused on the physiological effect of olfactory stimulation with Taiwan cypress oil [7], and several other reports have been published since. In recent years, the physiological relaxation effects of stimulation by olfactory stimuli such as air-dried hinoki cypress (hereinafter called "hinoki") (*Chamaecyparis obtusa*) wood chips [8], α-pinene [9], and $_{D}$-limonene [10], which are components derived from wood, have been reported. Several studies on visual stimulation have also been conducted using

Harumi Ikei and Chorong Song are co-first authors who contributed equally to this work.

Part of this study was presented at the 67th Annual Meeting of the Japan Wood Research Society, Fukuoka, March 2017.

✉ [redacted]

rooms with different designs and proportions of wood [11–13] and large wall panels [14]. In contrast, there have been extremely few reports on tactile stimuli.

Regarding the physiological effects of tactile stimulation by wood, Morikawa et al. [15] reported differential effects on blood pressure from touching plates of hinoki wood vs. artificial material. Sakuragawa et al. [16] examined differences in the effects of tactile stimulation on human physiology that resulted from materials at different temperatures (cool, room temperature, and warm). They found that touching an aluminum plate increased blood pressure, but the increase was inhibited when the aluminum was warmed; touching an acrylic plastic plate increased blood pressure, and a greater rate of increase was observed when the acrylic was chilled; and blood pressure did not change in response to touching objects made of hinoki, Japanese cedar, or oak, and did not increase even when the oak was chilled. These reports are pioneering studies on the physiological effects of tactile stimulation with wood on humans. However, they have limitations in that they only examined blood pressure, which is an index of autonomic nervous activity, as a measure of the physiological response to stimuli.

In our previous research, we examined the physiological effects on brain activity and autonomic nervous activity of touching wood with the palm of the hand [17, 18]. As an indicator of brain activity, oxyhemoglobin (oxy-Hb) concentration was measured in the left/right prefrontal cortex using near-infrared time-resolved spectroscopy (TRS). Heart rate variability (HRV) was used as an indicator of autonomic nervous activity. White oak, a broad-leaved tree generally used as an interior material, was used as a sample. The results indicated that touching uncoated white oak wood with the palm calmed prefrontal cortex activity [17, 18], increased parasympathetic nervous activity [17, 18], and decreased heart rate [18] more than did various building materials [17] and coated wood materials [18], thereby inducing physiological relaxation. However, there have been no reports of the effects on physiological responses of tactile stimulation (with the palm of the hand) by wood of coniferous trees.

This study, therefore, aimed to clarify the physiological effects of touching hinoki, which is one of the typical coniferous trees, with the palm of the hand in comparison with touching marble, a natural, nonwood building material. As physiological responses, brain activity (oxy-Hb concentration in left/right prefrontal cortex assessed with TRS) and autonomic nervous activity (sympathetic/parasympathetic nervous activity, assessed by HRV, and heart rate) were measured.

Materials and methods

Participants

The study participants were 22 female university students (mean age 21.1 ± 0.2 years). We excluded smokers, those currently in treatment for disease, and those who had menstrual periods during the study period. The participants were informed about the aim and procedures of the experiment before providing written informed consent to participate. Informed consent was obtained from all individual participants. The study was performed in accordance with the regulations of the Ethics Committee of the Center for Environment, Health and Field Sciences, Chiba University, Japan (Project Identification Code Number 5).

Study protocol

Physiological measurements were performed in a chamber with an artificial climate maintained at 25 °C, 50% relative humidity, and 230 lx illumination. In the waiting room, the participants received a description of the experiment and then moved into the chamber. After sensors for physiological measurement were fitted to the participant's forehead and chest, they received a description of the measurement procedure while in a seated position. Next, they practiced touching the stimulus with their palm using a dummy sample (sheet laminated flooring). Sheet laminate flooring was selected as a dummy sample since it is an artificial material used as an interior material in general. The experimental procedure was as follows. Participants rested with their eyes closed for 60 s (Fig. 1, left). Upon receiving instructions from the experimenter, they moved their right forearm using their elbow as a fulcrum and placed the palm on the stimulus (hereafter referred to as the "material") with their eyes closed for 90 s (Fig. 1, right). After touching the material for 90 s, they returned their hand to the previous position with their eyes closed upon the experimenter's instruction (Fig. 1, left). The experimenter then replaced the current material with the subsequent material, hid it with a cloth, and instructed participants to open their eyes. Subsequently, participants completed the subjective evaluation test. Figure 2 shows the experimental schedule. The materials were presented in a counterbalanced order to eliminate any effects due to the order of tactile stimulation. The physiological responses were measured continuously.

Tactile stimulation

Hinoki (*Chamaecyparis obtusa*) wood grown in Shizuoka Prefecture, Japan, was used as the base material. Three

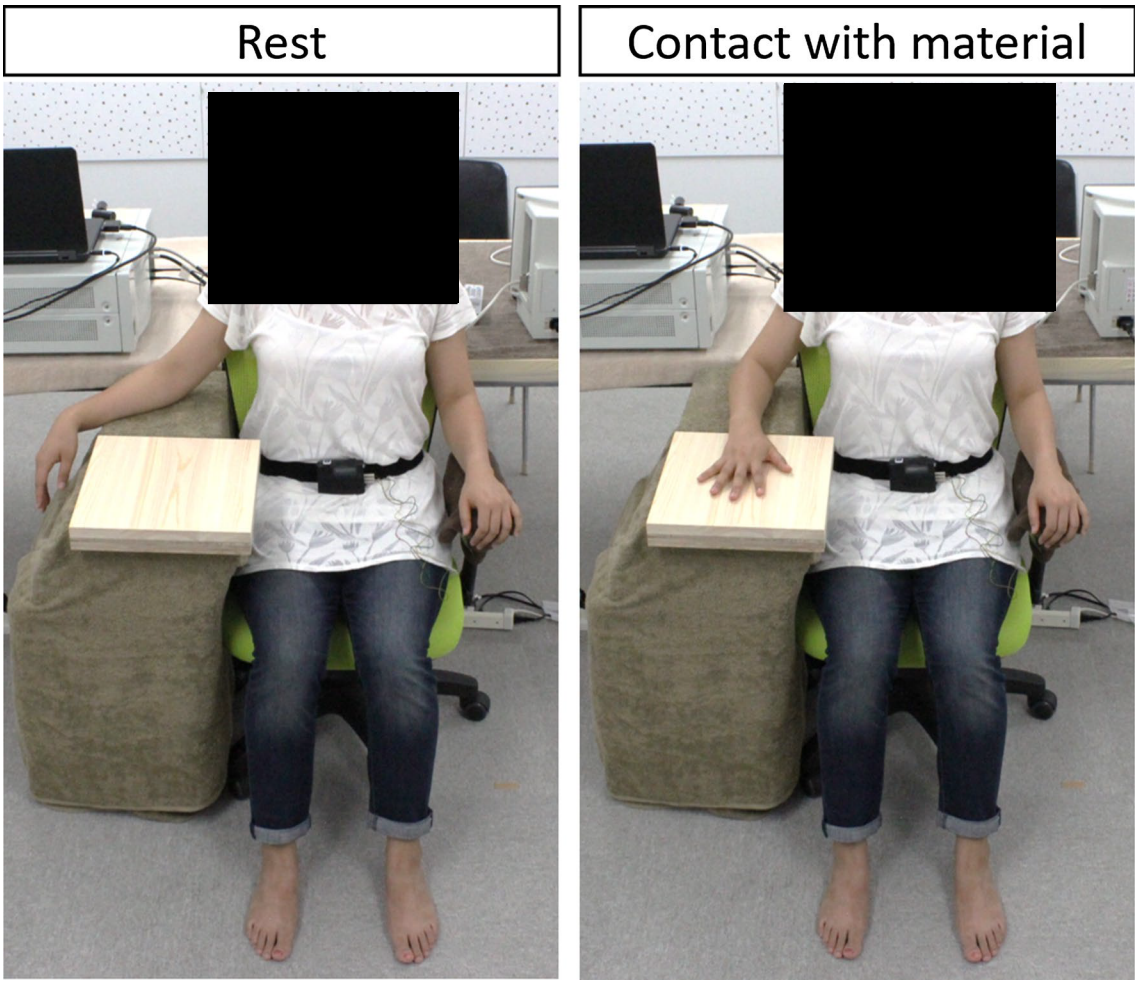


Fig. 1 Experimental setup

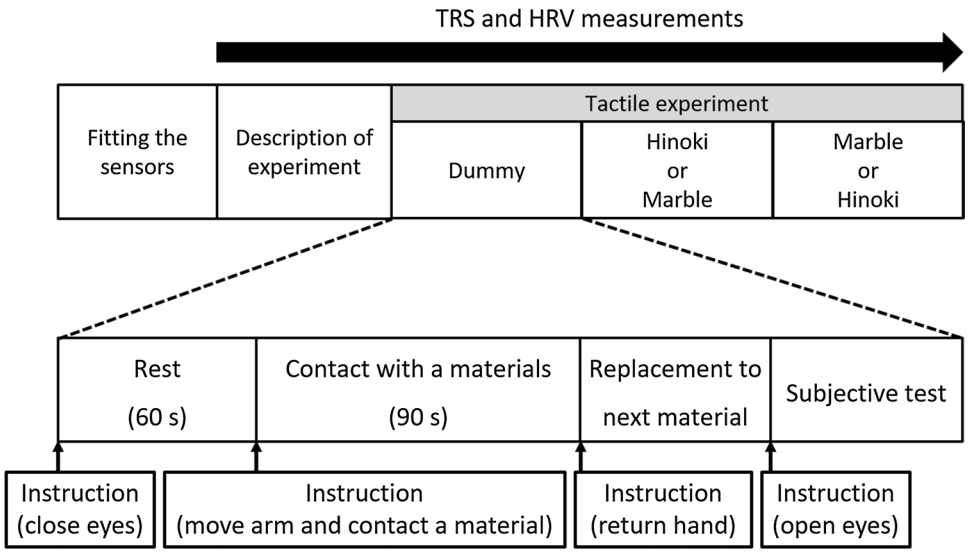


Fig. 2 Experimental schedule. *TRS* near-infrared time-resolved spectroscopy, *HRV* heart rate variability

laminae without vertical joints (size of each lamina = length 300 × width 100 × thickness 20 mm) were mutually bonded using a water-based polymer isocyanate adhesive along the width of each wood plate. To prevent bending, a second bonding was performed using Japanese cedar (*Cryptomeria japonica*) plywood (length 300 × width 300 × thickness 25 mm); the total thickness of the material was 45 mm. The surface of the hinoki material was finished by brushing it with a stainless steel wire brush (Fig. 3a).

As a control material, marble, which is used as a building material, was selected. The size of the marble material was 300 × 300 × 20 mm. It was placed on a piece of cedar plywood of the same size as those that were bonded to the hinoki, and presented to the participant. The surface was processed by buffing (Fig. 3b).

Although the surface roughness of materials varies widely depending on differences in sanding methods, both samples used in this experiment were evaluated in their general original state.

All materials were kept at room temperature. The physical properties of the materials are shown in Table 1.

Table 1 Details of samples

Material	*h* (mm)	*λ* (W/(mK))[a]	*ρ* (g/cm^3)[b]	*Ra* (μm)[c]	Condition
Hinoki	20 (+JCP 25)	0.133	0.52	54.74	Brushing
Marble	20 (+JCP 25)	0.186	1.87	0.08	Buffing

h thickness of material, *λ* thermal conductivity, *ρ* density of material, *Ra* arithmetic average roughness, *JCP* Japanese cedar plywood

[a]A heat flow meter (HFM 436 Lambda; NETZSCH, Selb, Germany), tuned according to ASTM C518-10 [19] and ISO8310 [20], was used. The direction of heat flow was vertically downward. The temperatures of the high- and low-temperature heat plates were 35 and 15 °C, respectively. The thermal conductivity at an average material temperature of 25 °C was calculated. The test specimens were used with the cedar plywood attached

[b]The samples were cured under the same environmental conditions as used in the thermal conductivity measurement; the mass was measured, and the density calculated. The samples with the cedar plywood adhered were used

[c]A contact surface roughness profilometer (SE3500; Kosaka Laboratory Ltd., Tokyo, Japan) with a diamond needle was used. The evaluation length was 50 mm. The central portion of the samples was measured five times with 50-mm spacing, and the average value was calculated

Physiological measurements

TRS

TRS, which is a near-infrared spectroscopy method, was used as an indicator of brain activity. Sensors were mounted on the participant's forehead, and oxy-Hb concentrations in the prefrontal cortex were measured by a TRS-20 system (Hamamatsu Photonics K.K., Shizuoka, Japan) [21–23]. The oxy-Hb concentrations in the left and right prefrontal cortex were measured before the participant touched the materials (premeasurement) and during the 90 s during which the participant touched the materials (postmeasurement). Because all data were obtained at approximately 1.0–1.2 s, they were transformed by linear interpolation every 1 s. In addition, all data were calculated as the difference between the averages of the 30-s values before touching.



Fig. 3 Materials used in the tactile experiment. **a** Uncoated hinoki wood; **b** marble material

HRV and heart rate

HRV and heart rate were used as indicators of autonomic nervous activity. HRV was analyzed during the periods between consecutive R waves (R–R intervals) on electrocardiograms measured with a portable electrocardiograph (Activtracer AC-301A; GMS, Tokyo, Japan) [24, 25]. The power levels of the low-frequency (LF) (0.04–0.15 Hz) and high-frequency (HF) (0.15–0.40 Hz) components of HRV were calculated using the maximum-entropy method (MemCalc/Win; GMS, Tokyo, Japan) [26, 27]. HF power reflected parasympathetic nervous activity, and the LF/HF ratio reflected sympathetic nervous activity [28, 29]. To normalize HRV parameters across participants, natural logarithmic-transformed values were used in the analysis [30]. The values of ln(HF), ln(LF/HF), and heart rate represented the changes that occurred in each 30 s and the overall mean during the 90 s in which participants touched the materials.

Psychological measurement

The modified semantic differential (SD) method [31] was used to evaluate the psychological effects of touching the two samples. The SD method tests the subjective evaluations of participants through a questionnaire with opposing adjectives, each of which is evaluated on a 13-point scale. Seven pairs of adjectives were assessed: "comfortable–uncomfortable", "relaxed–awakening", "natural–artificial", "warm–cold", "uneven–flat", "dry–moist", and "soft–hard".

Statistical analysis

Statistical Package for Social Sciences software (v21.0, IBM Corp., Armonk, NY, USA) was used for all statistical analyses. In all cases, $p < 0.05$ was taken to indicate statistical significance.

In physiological indices, regarding changes in each 30 s, paired t tests with Holm correction [32] were used to compare physiological responses between hinoki and marble materials; thus, the Holm correction [32] was applied three times. The Holm correction procedure is as follows. First, all p values are sorted by size and then compared with increasing limits. The lowest limit is the overall limit divided by 3; the smallest p value is to be compared with 0.05/3 or ca. 0.017. The second smallest p value is to be compared with $0.05/2 = 0.025$. The third smallest p value is to be compared with $0.05/1 = 0.05$. Null hypotheses can be rejected if the corresponding p values are less than the corresponding limit. However, this only applies until the limit is exceeded for the first time.

Regarding the overall mean in 90 s, paired t tests were used to compare physiological responses before and after touching each material (i.e., pre- vs. postmeasurement) and between hinoki and marble materials. In psychological indices, Wilcoxon signed-rank tests were applied to analyze the differences in psychological indices between hinoki and marble materials.

One-sided tests were used for all comparisons because our hypothesis was that humans would be more relaxed after touching the wood than after touching the other materials.

Results

Physiological effects

TRS

Figure 4a shows the changes in the oxy-Hb concentration in the left prefrontal cortex while the participant was touching hinoki and marble materials. Between 0 and 1 s (immediately after touching) and between 29 and 30 s, the oxy-Hb

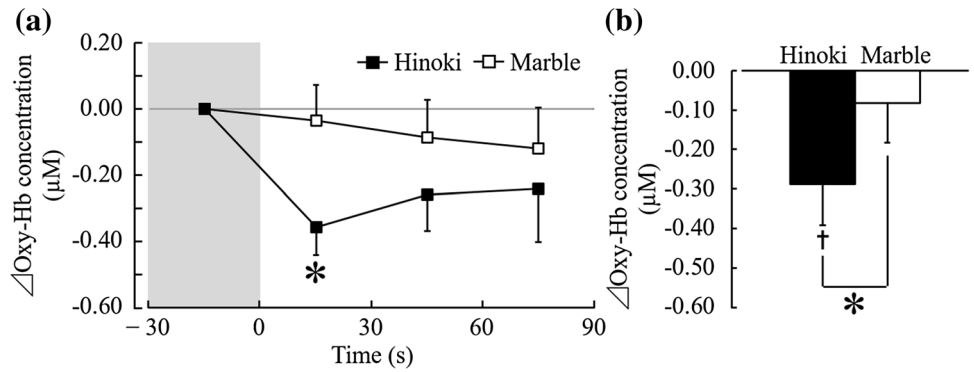


Fig. 4 Thirty-second average and overall mean oxyhemoglobin (oxy-Hb) concentration in left prefrontal cortex while touching hinoki or marble materials. **a** Changes in each 30-s average oxy-Hb concentration over 90 s. **b** Overall mean oxy-Hb concentration. Data are expressed as means ± standard error, $n = 22$, $^{\dagger}p < 0.05$ (comparing pre- vs. postmeasurement value), $^{*}p < 0.05$ (comparing hinoki vs. marble materials) as determined by the paired t test (one-sided); the Holm correction was applied

concentration was -0.36 ± 0.08 μM during contact with hinoki and -0.04 ± 0.11 μM during contact with marble; analysis of the difference indicated that the oxy-Hb concentration was significantly decreased after touching hinoki compared with marble (Fig. 4a, $p < 0.05$). Figure 4b shows a comparison of the average differential (post- to premeasurement) oxy-Hb concentration value in the left prefrontal cortex while the participant was touching hinoki and marble materials. Oxy-Hb concentrations in the left prefrontal cortex was -0.29 ± 0.10 μM for hinoki and -0.08 ± 0.10 μM for marble. Touching hinoki significantly decreased oxy-Hb concentration compared with touching marble (Fig. 4b, $p < 0.05$). The oxy-Hb concentration was also significantly decreased after touching hinoki compared with the premeasurement value (Fig. 4b, $p < 0.05$). Incidentally, the mean baseline for 30-s oxy-Hb concentration before touching did not significantly differ between hinoki and marble materials (43.67 ± 1.24 μM for hinoki and 43.27 ± 1.31 μM for marble; $p > 0.05$).

However, in comparisons between the pre- and post-measurement values and between hinoki and marble, there were no significant differences in oxy-Hb concentration in the right prefrontal cortex (-0.20 ± 0.11 μM for hinoki and -0.17 ± 0.09 μM for marble; $p > 0.05$).

HRV and heart rate

Figure 5a shows the changes in ln(HF) values, which reflect parasympathetic nervous activity, between touching hinoki and marble materials. Between 0 and 1 s and between 29 and 30 s, the ln(HF) value was 6.47 ± 0.20 lnms^2 during contact with hinoki and 6.13 ± 0.19 lnms^2 during contact with marble; analysis of the difference indicated that ln(HF) was significantly increased after touching hinoki compared with marble (Fig. 5a, $p < 0.05$). Figure 5b shows a comparison of the average ln(HF) values while touching hinoki and marble materials. The ln(HF) values were 6.31 ± 0.19 lnms^2 for hinoki and 6.08 ± 0.20 lnms^2 for marble. Touching hinoki significantly increased ln(HF) compared with touching marble material (Fig. 5b, $p < 0.05$). Incidentally, the mean baseline for 30 s ln(HF) before touching did not significantly differ between hinoki and marble materials (6.09 ± 0.23 lnms^2 for hinoki and 6.07 ± 0.18 lnms^2 for marble; $p > 0.05$).

However, in comparisons between hinoki and marble, there were no significant differences in the ln(LF/HF) ratio, which is an index of sympathetic nervous activity (0.96 ± 0.03 for hinoki and 0.94 ± 0.03 for marble; $p > 0.05$), and heart rate (68.45 ± 1.59 beats/min for hinoki and 68.10 ± 1.64 beats/min for marble; $p > 0.05$).

Psychological effects

The results of subjective evaluation by the modified SD method are shown in Fig. 6.

With regard to "comfortable" feeling, the participants reported subjectively feeling "slightly comfortable" after touching hinoki and "indifferent" after touching marble. Therefore, touching hinoki was believed to induce significantly more comfort than touching marble (Fig. 6a, $p < 0.01$). With regard to "relaxed" feeling, the participants reported subjectively feeling "slightly relaxed" while touching hinoki and "indifferent to slight awakening" while touching marble. Thus, hinoki induced significantly more relaxation than marble (Fig. 6b, $p < 0.01$). With regard to "natural" feeling, hinoki was perceived as "slightly to moderately natural", which was significantly more natural than marble, which was perceived as "slightly to moderately artificial" (Fig. 6c, $p < 0.01$). With regard to "warm–cold" feeling, the participants reported feeling "indifferent to slightly warm" after contact with hinoki and "moderately to very cold" after touching marble. Therefore, it was reported that touching hinoki was perceived as significantly warmer than touching marble (Fig. 6d, $p < 0.01$). With regard to "uneven–flat" feeling, hinoki, which was perceived as "slightly to moderately

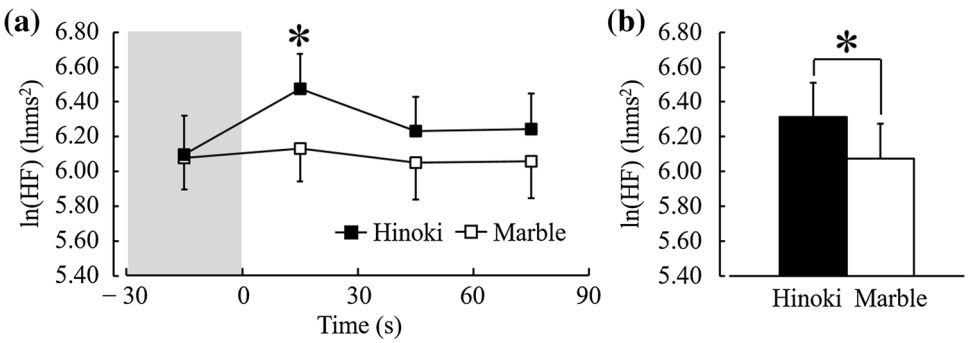


Fig. 5 Thirty-second averages and overall mean of the natural logarithm of the high-frequency (HF) component of heart rate variability (HRV) while touching hinoki or marble materials. **a** Changes in each 30-s average HF value over 90 s. **b** Overall mean HF values. Data are expressed as means ± standard error, $n = 22$, $^*p < 0.05$ (comparing hinoki vs. marble materials) as determined by the paired t test (one sided); the Holm correction was applied

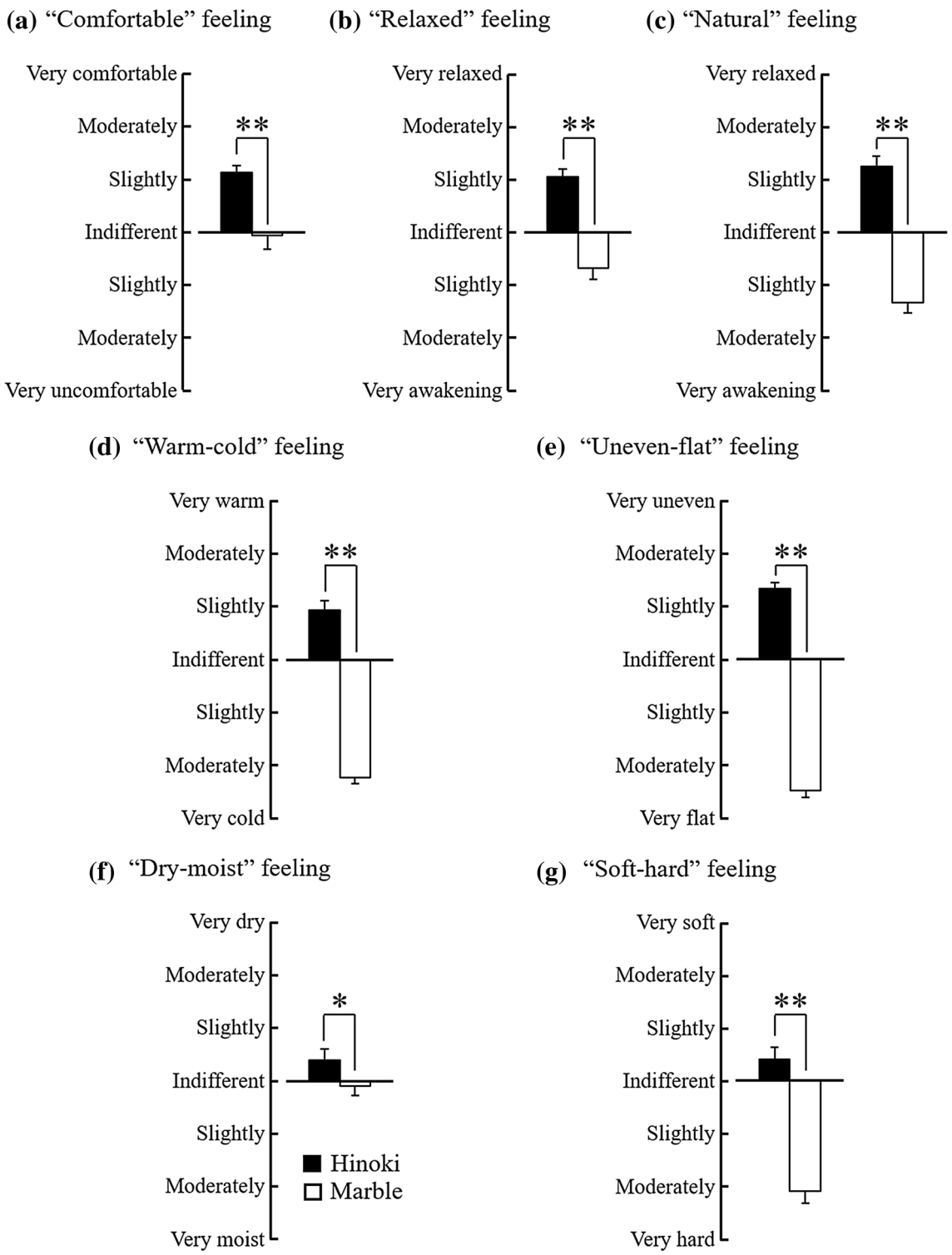


Fig. 6 Subjective feeling measured by the modified semantic differential method after touching hinoki or marble materials. **a** "Comfortable" feeling, **b** "relaxed" feeling, **c** "natural" feeling, **d** "warm–cold" feeling, **e** "uneven–flat" feeling, **f** "dry–moist" feeling, **g** "soft–hard" feeling. Data are expressed as means ± standard error, $n = 22$, $^{**}p < 0.01$, $^{*}p < 0.05$ as determined by the Wilcoxon signed-rank test; the Holm correction was applied

uneven", was considered significantly more uneven than marble, which was perceived as "moderately to very flat" (Fig. 6e, $p < 0.01$). With regard to "dry–moist" feeling, the participants reported feeling "indifferent to slightly dry" after contact with hinoki and "indifferent" after contact with marble, representing a significant difference (Fig. 6f, $p < 0.05$). Finally, with regard to "soft–hard" feeling, hinoki, which was perceived as "indifferent to slightly soft", was considered significantly harder than marble, which was perceived as "moderately hard" (Fig. 6g, $p < 0.01$).

Discussion

This study aimed to clarify the effects of touching hinoki wood with the palm of the right hand on left and right prefrontal cortex activity, assessed by TRS, and on autonomic nervous activity, assessed by HRV. The results showed that in comparison with the control (touching marble material), touching hinoki wood significantly decreased the oxy-Hb concentration in the left prefrontal cortex and significantly increased parasympathetic nervous activity according to the 90-s overall mean values. In addition, in subjective evaluations, we observed differences between hinoki and marble materials in terms of "comfortable", "relaxed", "natural", "warm–cold", "uneven–flat", "dry–moist", and "soft–hard" feelings, and these psychological findings were shown to be consistent with the physiological responses.

Regarding the physiological effects of tactile stimulation of wood with the palm, Ikei et al. [17] examined the effects of tactile stimulation with uncoated white oak wood on brain activity and autonomic nervous activity in comparison with other materials (marble, tile, and stainless steel). The participants touched the surface of each material for 90 s while sitting with their eyes closed. The results indicated that tactile stimulation with white oak significantly decreased oxy-Hb concentration in the left and right prefrontal cortices relative to marble, tile, and stainless steel and increased ln(HF)-reflected parasympathetic nervous activity relative to marble and stainless steel, thereby inducing physiological relaxation [17]. In addition, Ikei et al. [18] reported differences in the effects of tactile stimulation with uncoated white oak and various coated (oil-finished, vitreous-finished, urethane-finished, and mirror-finished) white oak materials. The results indicated that tactile stimulation with uncoated wood for 90 s calmed prefrontal cortex activity (vs. urethane-finished and mirror-finished wood), increased parasympathetic nervous activity (vs. vitreous-finished, urethane-finished, and mirror-finished wood), and decreased heart rate (vs. mirror-finished wood), demonstrating a physiological relaxation effect of wood on humans. Further, tactile stimulation with oil- and vitreous-finished wood, which retain the texture of natural (i.e., uncoated) wood, calmed left prefrontal cortex activity and decreased heart rate relative to mirror-finished wood [18]. Our findings on tactile stimulation with hinoki wood are, therefore, consistent with those of previous studies on tactile stimulation by natural wood or near-natural coated wood, demonstrating a physiological relaxation effect of touching wood with the palm of the hand.

Several studies have reported the physiological effects of olfactory stimulation from hinoki, which are consistent with the findings of our research [8–10, 33]. Olfactory stimulation with air-dried hinoki wood calmed prefrontal cortex activity compared with high-temperature-dried wood [8]. Olfactory stimulation with hinoki leaf oil calmed prefrontal cortex activity and increased parasympathetic nervous activity compared with the control condition (air), indicating that olfactory stimulation with hinoki leaf oil can induce physiological relaxation [33]. Inhalation of α-pinene [9] and D-limonene [10], which are major odorous components of coniferous trees such as hinoki, increased parasympathetic nervous activity and decreased heart rate compared with control condition (air), indicating physiological relaxation.

To explain this phenomenon, Miyazaki has advocated a "back to nature" theory [34, 35]. In this theory, he claims that human physiological functions are best adapted to a natural environment, because over 99.99% of the course of human evolution since our ancestors started evolving from a subset of primates into our current form around 6 to 7 million years ago has been spent in a natural environment. Conversely, we have spent less than 0.01% of human history in a modern environment, which only started with the beginning of urbanization in the Industrial Revolution. The highly urbanized and artificial environments that we currently inhabit are the root cause of the "stress state" of modern people. We, therefore, enter a relaxed state when exposed to the natural environment or to nature-derived stimulation, which brings us closer to our original natural state as human beings.

In this study, it is thought that tactile stimulation by touching hinoki wood with the palm of the right hand brought about physiological relaxation effects, because wood is a familiar and representative natural material for humans. Previous studies have shown that natural environments or nature-derived stimuli, such as forests [36–42], urban parks [43–45], flowers [46–50], and foliage plants [51, 52], induce physiological relaxation in humans. Wood is a familiar natural material which we have many opportunities to touch on a daily basis, and it is used for many household objects, such as interior materials of buildings and houses, furniture (desks and shelves), and stationery. Wood could become one of the effective materials for relieving stress in our modern urban, artificial society. Hinoki, which was used as a wood sample in this study, is one of the representative coniferous trees in Japan and has been used for a long time as a building material for shrines

and temples, such as the Horyuji Temple, whose pagoda is one of the oldest wooden buildings. Even today, hinoki is used for interiors, such as residential floors and walls.

The novel features of this study are that it dealt with tactile stimulation, for which there are limited physiological data; it used hinoki, which has not been the target of previous studies, as a material; and it conducted simultaneous measurement of prefrontal cortical activity and sympathetic/parasympathetic nervous activity to study the relaxation effects of the material.

In summary, our results show a physiological relaxation effect of tactile contact with hinoki wood, which is one of the representative coniferous trees in Japan. However, the study has certain limitations. First, although we examined the effect of touching wood with the palm of the hand, we did not examine the effect of contact with other body surfaces. Future research should examine the effect of wood on physiological response when it is touched with the sole of the foot, because wood is often used as a flooring material. Second, this study only measured the physiological effects of wood from placing the palm of the hand on the stimulus. It will be necessary to clarify the impact on the physiological response of more active forms of contact, such as stroking the surface of the wood with the hand. Finally, although this study compared noncoated hinoki wood with a nonwood material (marble), it will be necessary to determine the effect of touching hinoki wood with various coatings on the physiological response, because much of the wood used in everyday life is coated.

Conclusions

Touching hinoki with the palm of the right hand significantly decreased the oxy-Hb concentration in the left prefrontal cortex and increased ln(HF)-reflected parasympathetic nervous activity compared with touching marble. These findings indicate that tactile stimulation of the palm of the hand with hinoki wood calms prefrontal cortex activity and increases parasympathetic nervous activity, thereby inducing physiological relaxation.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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Horticultural Activity: Its Contribution to Stress Recovery and Wellbeing for Children

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Abstract: In recent years, children's use of mobile phones has grown rapidly, which might lead to an increase in mental stress and negatively affect their health. Despite increasing evidence that horticultural activity can provide significant health benefits, few scientific evidence-based studies are currently available regarding these benefits to children's health and wellbeing in schools. Therefore, this study aims to determine the potential benefits of horticultural activity for children from both psychological and physiological perspectives. Twenty-six elementary school students (mean age, 8.12 ± 0.21 years) were asked to perform a plant-related task and a mobile game task for 5 min. During both tasks, physiological sensors were used to measure the participants' heart rate variability, skin conductance, and skin temperature. Additionally, the participants' emotional responses were assessed using semantic differential and State–Trait Anxiety Inventory tests immediately after each task. Results revealed that, compared with the mobile game task, participants' health statuses were positively correlated with the horticultural task, including a considerable decrease in skin conductance and sympathetic nervous activity, together with a marginal increase in parasympathetic nervous activity. Such responses suggested that horticultural activity increased relaxation and decreased feelings of stress. Furthermore, the horticultural activity was associated with a substantial increment in comfort, naturalness, relaxation, and cheerfulness feelings, as well as a significant reduction in depression and a reduction in total anxiety levels. Given these positive benefits, horticultural activity may provide a great contribution to children's healthy life at school, prompt psychological relaxation and minimize mental stress relative to smartphone games.

Keywords: children; relaxation; horticulture activity; horticulture therapy; heart rate variability; wellbeing

1. Introduction

The World Health Organization (WHO) (2006) defined health as "a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity" [1]. Soga and collogues defined "health" in a wide meaning, including physiological and psychological wellbeing [2]. Importantly, individuals' modern-day lifestyle, which includes long hours indoors and unconscious isolation from nature, can cause serious problems for individuals' health and wellbeing [3]. Most individuals' mental health problems (such as depression, anxiety, stress, anger, and sadness) are attributed to their limited exposure to natural environments [4].

Less exposure to nature and green spaces can increase the vulnerability of individuals to the effects of stressful life events and environmental stressors that influence physiological and psychological health [5]. Nature in cities plays an important role in promoting a healthy society [6]. The theories of Kaplan [7] and Ulrich [8] support the idea that rehabilitation from attentional fatigue and stress

is effectively facilitated by natural environments. There is growing evidence that direct exposure to natural environments provides a wide range of health benefits [9–11]. The fact that daily contact with nature can improve individuals' health and be used as a form of preventive medicine is increasingly being recognized [6]. These findings particularly support the argument that contact with nature, plants and horticultural activities can improve human health and wellbeing, giving support to both Attention Restoration Theory and Stress Recovery Theory. Attention Restoration Theory (ART) [7] suggests that exposure to nature can help us improve our focus and ability to concentrate. Stress Reduction Theory (SRT) [8] proposes that exposure to nature may have a direct restorative effect on cognition and may reduce stress.

A recent study showed that children spend more than 7 hours a day engaged in different media activities (e.g., smartphones, Internet and TV)—more time than they spend in studying or sleeping, which leads to increased psycho-physiological stress [12]. Additionally, surveys conducted in the USA reported that about 1 of every 4 children will experience mental stress and that about 1 in 10 will have a serious emotional disturbance [13]. Such psycho-physiological stress may lead to significant reductions in cognitive performance. Children, however, can recover from stress, retrieve cognitive efficiency and promote their health by taking advantage of the benefits resulting from exposure to nature [5].

Horticultural activity is one of the most common ways to interact with nature and is enjoyed in many countries as a popular pastime [2]. In mental health, activities relating to nature (e.g., horticulture and gardening) offer opportunities to strengthen various health and wellbeing facets, foster positive interpersonal relationships that improve social inclusion, and encourage mental illness destigmatization [14]. Increasing focus has been given to the beneficial impacts of nature-related activities, such as gardening or horticultural activities, which are regarded as a promoter of health and wellbeing [15]. Scientists and health practitioners are increasingly aware of the potential health benefits resulting from gardening practices [16,17]. Earlier studies have demonstrated that gardening improves individual life satisfaction, wellbeing, positive emotions, community social work, and cognitive function [18,19]. A decline in symptoms of stress, anger, depression and anxiety have also been documented [18,20]. Consequently, involvement in gardening has become more widely recognized as a cost-effective health treatment [16] as well as a treatment or occupational therapy for people with psychological health problems, called "horticultural therapy" [21].

Previous studies have shown the physiological and psychological benefits that occur in adults after horticultural and gardening activities [2,22]. Horticultural activities have proven to be excellent personal and community activities that promote and enhance the wellbeing of elderly people [23]. Despite these positive impacts, surprisingly, to date, little physiological and psychological evidence is available on the positive impacts of horticultural activity on children's wellbeing. More comprehensive and convincing evidence is still needed. Louv's study [24] concluded that a decline in interaction with nature has contributed to a number of health and behavioral problems, especially for children, which can, in short, constitute a "nature-deficit disorder". Hence, this research focused on the benefits of horticultural activity on children's health and wellbeing.

Therefore, the objective of this study is to investigate the psychological and physiological relaxation impacts of horticultural activity from a multi-dimensional perspective by recording heart rate variability (HRV), skin conductance (SC), skin temperature (SKT) and emotional responses in elementary students. Scientific analysis regarding the recorded data was carried out to provide rigorous evidence in support of the benefits of horticultural activity on children's wellbeing.

2. Materials and Methods

Ethical approval for the present study was obtained from the Ethics Committee of Tongji University (2019tjdx283). The informed written consent of the parents and/or guardians as well as the verbal consent of the students prior to participation were provided. The experiment was conducted between 20 and 25 December 2018.

2.1. Participants

Twenty-six elementary school students comprising 15 males and 11 females at the age of 8.12 ± 0.21 (mean ± SE) were recruited for this study. Experiment volunteer students were recruited using two different methods: (1) an e-mail detailing the study procedures was sent to the school director; (2) the researchers of the present study asked the students in person if they would like to participate. Selected participants obeyed the following criteria: no pre-existing physical and emotional disabilities that could influence physiological outcomes, no pre-existing heart-related condition and skin condition and no allergy to electrodes. The procedure of the experiment was fully explained to the participants prior to the beginning of the experiment.

2.2. Study Protocol

To investigate the participants' physiological and psychological responses, two tasks were introduced: first, stem cuttings were prepared from a real plant (one of the most common methods of the asexual propagation of plants) and cultivated in pots filled with soil, which was performed as a horticultural activity. Second, participants played a gardening game that simulated a realistic environment in which children can grow seeds and plants using smartphones as the comparison. Before the experiments, the author taught each participant the fine motor skills required, such as how to prepare cuttings (cutting with scissors) and how to cultivate them easily (planting) so that they could work more comfortably. The choice of the plant for cuttings was based on its availability in the area of the experiment. The activities took place in a quiet room in which the students rested after the study day. The room temperature was set at 21 °C ± 0.7 °C, mean ± SE; the relative humidity remained at 58.2% ± 2.5%; and the illuminance was 2000 lux.

To ensure that participants required relaxation, the experiment was conducted after a school day. The time of the study was coordinated with classroom supervisors so that the experimental days fitted students' schedules. Before starting the experiment, the process of the experiment and how to use the instruments were clearly introduced to the participants. The experiment design was within-subject, and both experimental conditions were experienced by each participant in a random sequence. Each participant was invited to sit on a chair while fitting the ErgoLAB sensors (Kingfar Technology Co. Ltd, Beijing, China) for HRV, skin conductivity and skin temperature measurements. Participants were then told to rest for 60 s to adapt their mood to the experimental environment and then asked to perform their assigned tasks of either a horticultural task or a smartphone game task for 5 min. At the beginning of the experiment, HRV, SC, SKT were recorded and continuously recorded until the end of each task. After that, each participant was asked to rate their emotional reaction and the level of anxiety for each task using two self-reported questionnaires: a semantic differential questionnaire (SD) and the State–Trait Anxiety Inventory (STAI). The participants were asked to relax again for a duration of 60 s after the completion of each task. The overall duration of the experiment was 27 min per subject (Figure 1).

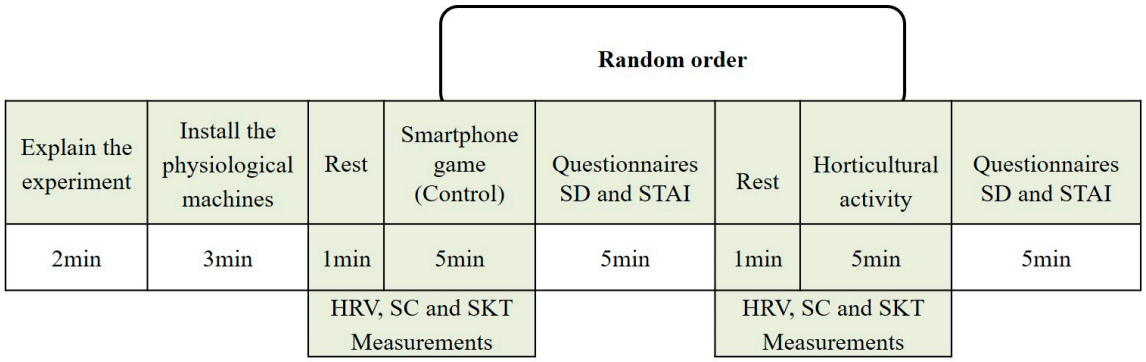


Figure 1. Study protocol. SD: semantic differential questionnaire; STAI: State–Trait Anxiety Inventory; HRV: heart rate variability; SC: skin conductance: SKT: skin temperature.

2.3. Physiological Measurements

The ErgoLAB synchronization platform (Kingfar technology Co. LTD, Beijing, China) was used to measure HRV, SC, and SKT. The ErgoLAB platform includes a set of portable sensors and a computer-based digital platform that is linked to a wireless receiver. Previous studies have verified the validity of ErgoLAB [25,26]

2.3.1. Heart Rate Variability

A recent review revealed that HRV is affected by stress and encouraged its use in assessing psychological stability and mental stress in an objective assessment [27]. HRV represents the sympathetic level (stress) or the feeling of parasympathetic (relaxation) activation [28]. HRV is a useful tool for measuring the sympathetic–parasympathetic balance of the autonomic nervous system [29]. A power spectral analysis of the beat-to-beat variations of heart rate has become commonly used to measure cardiac autonomic regulation [30]. This analysis divides the overall variation (the "power") of a continuous series of beats into its frequency components, usually defining two major peaks: a low-frequency band (LF) at 0.04–0.15 Hz (which is often thought to have a dominant sympathetic component) and a high-frequency band (HF) at 0.15–0.4 Hz (which represents cardiac parasympathetic nerve activity) [31]. In addition, the ratio of LF and HF (LF/HF) was determined as indicative of the sympathetic–parasympathetic nervous system activity ratio [31,32]. Lower HF power is correlated with stress, panic, anxiety, or worry [33]. A wireless wearable sensor, based on a photoplethysmogram (PPG) with a sampling frequency of 64 Hz, was attached to the participant's earlobe to measure HRV values, LF, HF and the LF/HF ratio. Filters were applied before analyzing HRV results and then replaced with ectopic values to evaluate the frequency domain. Typical filters are low-pass de-noise, white de-noise, baseline de-noise, and band stop. The natural logarithm (Ln) was applied to frequency domain data before analysis to transform the original data into a normal distribution [34].

2.3.2. Skin Conductance (SC)

Electrodermal activity, or sweating, has been long regarded as a measure associated with emotional arousal and stress. To measure the SC using the ErgoLAB platform, an electrodermal activity-based (EDA) wearable sensor with a 0–30 µs measurement range and 32 Hz sampling frequency was positioned on participants' fingertips, which are areas of the body densely populated with eccrine sweat glands [35]. Two sensor electrodes were connected to two left-hand fingertips. In order to apply a time domain evaluation to the EDA signals, filtering procedures and image deconvolution analysis were carried out prior to the evaluation to remove noise [36]. In general, the SC response has been reported to be correlated with emotional responses (and especially high arousal responses) [37]. Such responses are controlled by the sympathetic system, which in turn activates the sudomotor nerve, causing the release of sweat from the sweat glands in the skin of the hand [38,39].

2.3.3. Skin Temperature

The temperature of the skin is suggested to provide an indirect measure of activity in the sympathetic nervous system. A reduction in arousal results in an increase in vasodilation and blood flow to the peripheral areas of the body, demonstrated by an increase in skin temperature [35]. Previous work has shown that the temperature of the skin indicates the intensity of the stress [40]. A wireless skin temperature probe with a 10 °C to 60 °C measurement range, 0.1 °C precision, and 32 Hz sampling frequency was placed on the fingertip of the left hand to monitor temperature changes in the skin.

2.4. Psychological Measurements

Two self-reporting questionnaires were used during the experiment to evaluate the associated psychological reactions to each task.

2.4.1. Semantic Differential Questionnaire (SD)

Opposing adjectives were provided in the SD questionnaire: "comfortable to uncomfortable"; "natural to artificial"; and "relaxed to awakening" [41]. The question format was scored on a five-point scale (−2, −1, 0, 1 and 2) based on the emotional level. In this procedure, a higher score represented better emotional conditions.

2.4.2. State–Trait Anxiety Inventory (STAI)

To assess the volatility of the anxiety level following both activities, the State–Trait Anxiety Inventory (STAI) investigated the children's feeling "right now", with 20 questions used to evaluate the participants' corresponding feelings, such as tension, nervousness, and worry [42]; the higher the score, the more severe the anxiety [43].

2.5. Statistical Analysis

SPSS (Ver. 24; IBM Corporation, Armonk, NY, USA) was used to conduct a one-way ANOVA. Paired *t*-tests were used to compare physiological data, and for the psychological data, the Wilcoxon signed-rank test was used. A p-value of < 0.05 indicated statistical significance. All data were expressed as mean ± standard error.

3. Results

3.1. Physiological Measurements

3.1.1. Heart Rate Variability (HRV)

The mean of the sympathetic and parasympathetic nervous activities while engaging in the horticultural activity and the mobile game activity, along with the associated test results for statistical significance, are presented in Figures 2 and 3. The participants' high-frequency band (lnHF), which represents parasympathetic nerve activity, significantly increased during the horticultural activity compared with those measured during the mobile game task (3.42 ± 0.06 vs. 2.37 ± 0.08, $p < 0.01$, Figure 2). Furthermore, as shown in Figure 3, the mean lnLF/HF, which represents sympathetic nerve activity, significantly decreased during the horticultural activity compared with that measured during the mobile game task (0.16 ± 0.07 vs. 0.54 ± 0.04, $p < 0.01$). This outcome suggests that the state of relaxation of the participants was associated with the horticultural activity rather than the mobile game task.

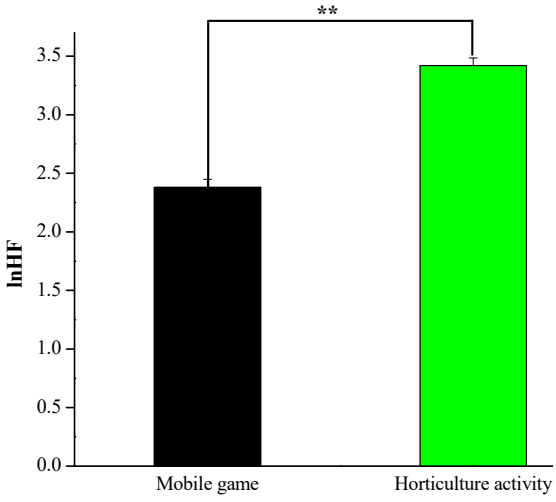


Figure 2. High-frequency band (lnHF) scores during the 5 min experimental period; $n = 26$, mean ± SE, ** $p < 0.01$ determined by the paired *t*-test.

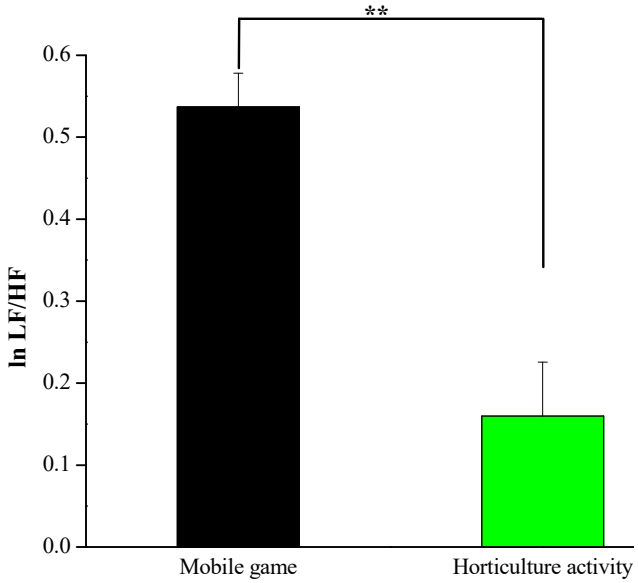


Figure 3. Ratio of low-frequency to high-frequency band (lnLF/HF) during the 5 min experimental period; $n = 26$, mean ± SE, ** $p < 0.01$ determined by the paired t-test.

3.1.2. Skin Conductance (SC)

Figure 4 shows the mean of the participants' skin conductance during the 5 min activity period. The participants presented lower SC averages during the horticultural task than during the mobile game task (5.48 ± 0.86 vs. 7.94 ± 1.40, $p < 0.01$). The results showed that the horticultural activity positively influenced the participants, as shown by noticeable declines in their skin conductance compared to the mobile game activity.

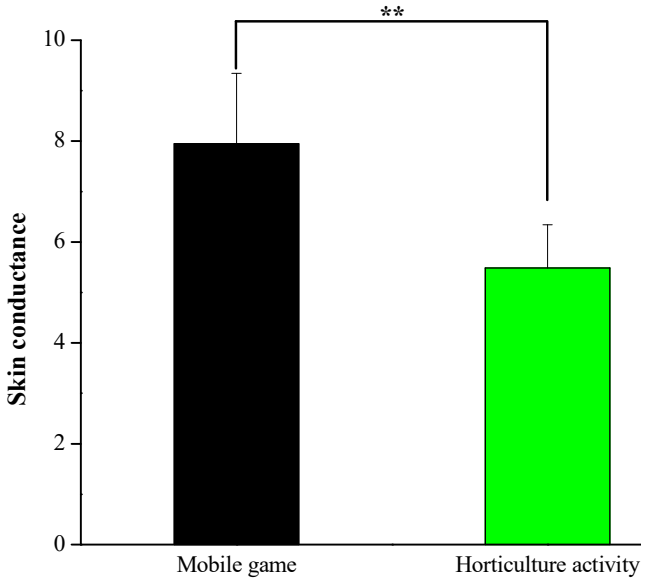


Figure 4. Mean of skin conductance during the 5 min experimental period; $n = 26$, mean ± SE, ** $p < 0.01$ determined by the paired t-test.

3.1.3. Skin Temperature (SKT)

During the 5 min experiment period, with a sampling frequency of 16 Hz, the ErgoLAB platform's wearable sensor was used to record the skin temperature of participants in the middle fingertip. Figure 5 shows that the two activities shared similar SKT mean values: horticultural activity, 30.47 ± 0.33 °C vs. mobile game, 30.60 ± 0.34 °C, $p > 0.1$.

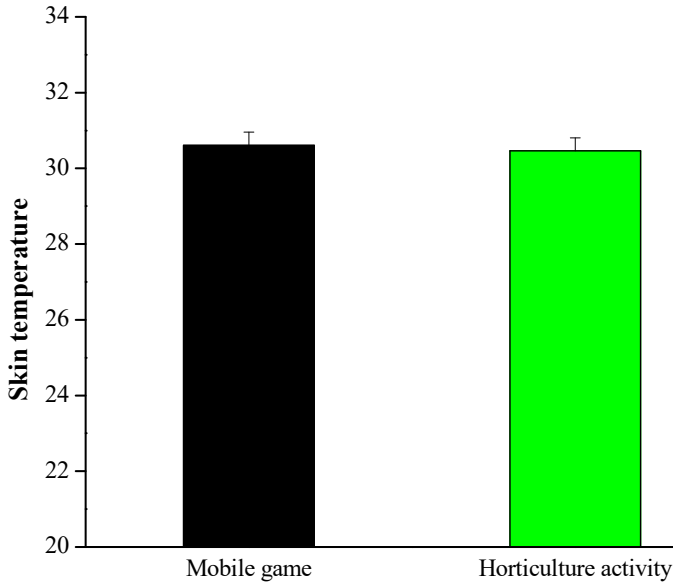


Figure 5. SKT during the 5 min experimental period; $n = 26$, mean ± SE, $p > 0.1$ determined by the paired *t*-test.

3.2. Psychological Measurements

3.2.1. Semantic Questionnaire (SD)

Semantic questionnaire data analysis revealed that emotions during the horticultural activity were different from those during the mobile game task. The participants felt more comfortable, relaxed, colorful and cheerful than after the mobile game task. Additionally, the participants expressed a strong preference for the horticultural task over the mobile task. There were significant differences between the two activities for the six feelings tested after the 5 min tasks ($p < 0.001$, Figure 6). Thus, engaging children in some horticultural activities may evoke more comfortable, relaxed, and positive feelings than playing games on phones.

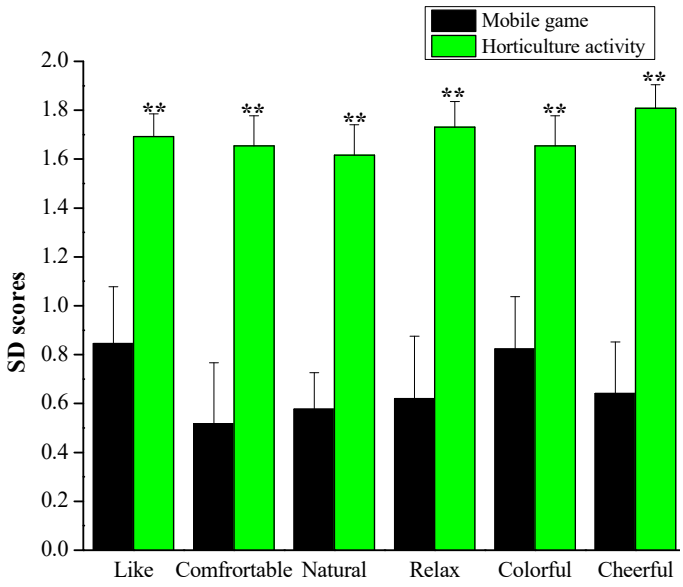


Figure 6. Comparison of the participants' SD scores between horticultural and mobile game activities. $n = 26$, mean ± SE, ** $p < 0.01$ according to the Wilcoxon signed-rank test.

3.2.2. State–Trait Anxiety Inventory (STAI)

The participants' mean anxiety scores were lower after the horticultural task compared with those after the mobile game task (39.09 ± 0.64 vs. 45.85 ± 0.52; $p < 0.01$, Figure 7). This finding revealed the potential of horticultural activity to reduce anxiety levels.

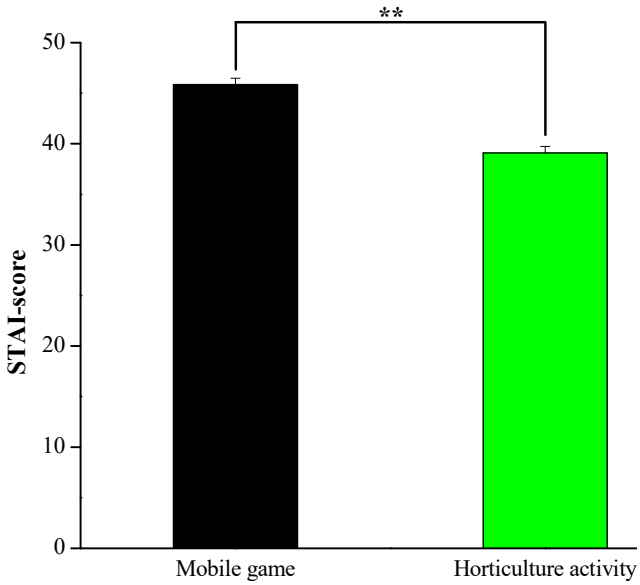


Figure 7. Comparison of participants' State–Trait Anxiety Inventory (STAI) scores between the two activities. $n = 26$, mean ± standard error. ** $p < 0.01$, determined by the Wilcoxon signed-rank test.

4. Discussion

The objective of the present study was to investigate the health benefits and the stress-reducing impacts of 5 min of horticultural activity on elementary school students by measuring their physiological functioning (HRV, SC, and SKT) and psychological responses using SD and STAI from different assessment dimensions. Prior studies have shown the importance of horticultural activity for adult males [22], females [44] and elderly people [45]; however, very little is known about its positive impacts for children.

Results showed that horticultural activity for 5 min resulted in lower LF power and higher HF powers than those obtained during the mobile game activity. Additionally, we found that the LF/HF ratio when the participants engaged in the horticultural activity was significantly lower than that obtained during the mobile game activity. It is interesting to note that horticultural activity significantly increased the children's parasympathetic nerve activity, which stimulates relaxation, and significantly decreased the sympathetic nervous activity, which alleviates stress. In contrast, the mobile task increased the participant's sympathetic nervous system activity. The results showed that horticultural activity could enhance children's wellbeing by increasing relaxation and reducing stress compared with the mobile game activity. The lower LF/HF ratio represents parasympathetic superiority, as seen when people engage in tend-and-befriend behaviors [33]. Furthermore, prior studies reported that LF/HF was more likely to be increased at discomfort level [10,22]. These results reflect those of Lee and colleagues who found a significant stress reduction when the participants were involved in horticultural activity [22].

Skin conductance is an additional indicator of emotional state and physiological arousal and is a concept used to describe the electrical characteristics of the skin. Previous studies showed that the sympathetic autonomic nervous system, which controls the sweat glands in the skin, is influenced by an increase in physio-psychological arousal [46] and stress [47], which in turn increases the skin conductivity. The outcomes demonstrated that skin conductance was considerably lower when the children were engaged in the horticultural activity in comparison with the mobile game activity,

indicating that they were more relaxed during the horticultural activity. The study by Ulrich showed that exposure to the natural environment has critical benefits for individuals' heart rate and skin conductance [8]. These results suggest that horticultural activity can have positive impacts on human stress response through the suppression of sympathetic nervous system activity. These positive benefits may result from multiple natural stimuli acting on the five senses: touch, vision, listening, smell and taste [48]. Viewing plants has been documented to provide a variety of advantages including reduced anxiety and reduced stress [49–52]. In addition, Koga and Iwasaki [53] showed that touching plants induced physiological and psychological relaxation. Physiological and psychological stress can be reduced by touch, as the physical sensation of touch affects the cardiovascular system resulting in lower blood pressure and heart rate [54]. Unexpectedly, during the 5 min task period, there was no significant difference in mean SKT scores between the two activities. This may have been due to the experimental room temperature and humidity [35].

Regarding the results of the semantic differential questionnaire, subjects indicated that they felt more "comfort", "relaxation", and "cheerfulness" after participating in the horticulture activity compared to the mobile game activity. In words, the SD scores showed that horticultural activity positively affects the participants' psychological states. Such results were consistent with Elsadek's study, which reported that viewing plants has a strong positive correlation with positive emotions [55]. Additionally, transplanting activities led to better emotional states and lower stress levels than computer tasks [22]. On the other hand, the findings of the STAI scores also indicate that lower levels of negative emotions such as tension, anxiety, worry, confusion and unhappiness were felt when performing the horticultural activity compared to the mobile game task, offering additional support for the beneficial impacts of horticultural activity for human health. Together with other studies' findings, the study results clarified that, when exposed to natural stimuli, participants are more likely to express lower levels of anxiety and negative emotions [56,57]. The self-reported questionnaires' results for the participants suggest that horticultural activity has positive effects on mental stress and can reduce psychological stress compared with the mobile game task.

It is worth emphasizing that the present study may support the beneficial physiological and psychological impacts of horticultural activity on children's wellbeing via a scientific experiment. Participants tended to relax more during the horticultural activity due to their enhanced physiological and psychological levels, which is compatible with the observation of self-assessment that the participants felt much more relaxed and comfortable when engaging in horticultural activity. Interestingly, the response detected by the heart rate variability findings is substantially compatible with the results for skin conductance, and the emotional responses that horticultural activity provided were positive influences on the participants' health and wellbeing. Two main theories that are useful in explaining the effect of horticultural activity on human wellbeing are Attention Restoration Theory [7] and Stress Reduction Theory [58]; both are based on the concept of biophilia—the idea that people have an innate need to be associated with the natural environment in which they have evolved. Although several studies have reported the positive impacts of horticultural activities [59–61], little attention has been given to children's responses. Our experiment provides relevant data, from the perspective of relaxation, that can clarify the mechanism behind the health benefits of horticultural activities for children. Interestingly, our study suggests that the engagement of children in horticultural activities in school could reduce stress and promote their physiological and psychological relaxation.

Given the strengths and weaknesses of the present study, a notable strength is that the results are based on multi-dimensional measurements; the research combined different aspects of the physiological measurements (HRV, SC and SKT) with psychological aspects (SD and STAI). Furthermore, the lack of studies on the relaxation effects of horticultural activity for children underpins the significance of our study. This study was subject to some limitations, including that our focus group was limited to healthy children; in the future, more children with health problems should be examined to generalize the findings. Our sample size was small; future studies should recruit more participants. Furthermore, a comparison of children's responses before/after the horticultural activity is needed, and we used only

short-time measurement; theoretically, a long-term task is needed. Future research should also use more realistic and practical activities concerning the application of findings.

5. Conclusions

The present study provided scientific support for the physiological and psychological impacts of horticultural activity on elementary school students. Horticultural activity for 5 min enhanced children's physiological relaxation by suppressing sympathetic nervous system activity and skin conductance compared with mobile use. Furthermore, the horticultural activity tended to relieve anxiety levels and bring several positive health benefits such as comfort, relaxation, cheerfulness and natural emotions for children. It was decisively shown that children could greatly benefit physiologically and psychologically from horticultural activity. In general, the results have important applications and great potential to be integrated as a daily program for students in schools.

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Comparing Concentration Levels and Emotional States of Children Using Electroencephalography during Horticultural and Nonhorticultural Activities

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Additional index words. electroencephalography, gardening, horticultural therapy, semantic differential method

Abstract. **This study aimed to compare the brain activity and emotional states of elementary school students during horticultural and nonhorticultural activities. A total of 30 participants with a mean age of 11.4 ± 1.3 years were included. This experiment was conducted at Konkuk University campus in Korea. Participants performed horticultural activities such as harvesting, planting, sowing seeds, and mixing soil. Nonhorticultural activities included playing with a ball, solving math problems, watching animation videos, folding paper, and reading a book. The study had a crossover experimental design. Brain activity of the prefrontal lobes was measured by electroencephalography during each activity for 3 minutes. On completion of each activity, participants answered a subjective emotion questionnaire using the semantic differential method (SDM). Results showed that relative theta (RT) power spectrum was significantly lower in both prefrontal lobes of participants when engaged in harvesting and reading a book. The relative mid beta (RMB) power spectrum was significantly higher in both prefrontal lobes when participants engaged in harvesting and playing with a ball. The ratio of the RMB power spectrum to the RT power spectrum reflects concentration. This ratio increased during harvesting activity, indicating that children's concentration also increased. The sensorimotor rhythm (SMR) from mid beta to theta (RSMT), another indicator of concentration, was significantly higher in the right prefrontal lobe during harvesting than during other activities. Furthermore, SDM results showed that the participants felt more natural and relaxed when performing horticultural activities than nonhorticultural activities. Horticultural activities may improve brain activity and psychological relaxation in children. Harvesting activity was most effective for improving children's concentration compared with nonhorticultural activities.**

Horticultural activities have a variety of positive effects on humans. According to previous studies that measured metabolic equivalents (METs) when performing horticultural activities, horticultural activities such as planting transplants, sowing seeds, harvesting, and mixing growing medium were found to provide a wide range of physical activity with low to high intensity (2.4–4.9 METs) (Park et al., 2011, 2013a, 2014a). Various horticultural activities use the large and small muscles of the upper and lower body (Park et al., 2013b, 2014b) and can effectively improve the functional ability of the hands (Park et al., 2020), thereby developing body strength and bone density as a result of weight-bearing exercises (Olivetti et al., 2007) and enhancing the overall physical functional ability (Han et al., 2018).

Horticultural activities allow individuals to develop emotional stability and express emotions naturally through their participation with groups (Relf, 1992). Various horticultural activity programs have been effective for improving children's emotional intelligence, resilience, and self-efficacy (Lee et al., 2020; Oh et al., 2020). Additionally, the stress index values for interpersonal, school, personal, and family problems of the horticultural activity group were decreased (Lee et al., 2018a). Furthermore, it has recently been found that horticultural activity can improve serum tryptophan, kynurenine, and serotonin levels, which serve as biomakers for improved cognitive ability (Park et al., 2020). Another study reported that children exhibited increased brain activity and concentration when tasks were performed in spaces where plants were located (Kim et al., 2020).

Previous studies have reported that the visual stimulation of green plants has positive effects on the psychological and physiological aspects of individuals. Park et al. (2016) and Ikei et al. (2014) reported that viewing foliage plants induced psycho-physiological relaxing effects by reducing prefrontal cortical activity and increasing parasympathetic activity and emotional states. Park et al. (2017) found that tasks involving living plants induced more physiological relaxation because the concentration of oxy-hemoglobin in the prefrontal cortex of the participants was lowered. Additionally, Choi et al. (2016) reported that only 5% of the indoor green index could improve the heart rate variability and stimulate the autonomic nervous system as measured by electroencephalography (EEG), thus providing benefits to physiological stability. However, the subjects of these studies are limited to adults and the elderly, and few studies have involved children. Because the psycho-physiological benefits of contact with plants may vary by age, this study aimed to identify the effects of horticultural activities on children's concentration and emotional states by measuring the EEG results.

Materials and Methods

Participants. This study involved 30 elementary school students between 10 and 13 years of age. In previous studies investigating the psycho-physiological effects of exposure to plants on humans, 30 participants were recruited as a single experimental group without a control group and showed significantly different results (Kim et al., 2020; Oh et al., 2019). Research information was posted on the bulletin boards of churches and apartments near Konkuk University to recruit participants. Students who wished to participate in the study were required to provide a consent form from their parents. The inclusion criterion was right-hand dominance because hand gestures between the dominant and nondominant hand differ during cortical activity (Tarkka and Hallett, 1990). Additionally, participants were required to fast for 2 h before the experiment. According

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to a study by Heckman et al. (2010), caffeine and other ingredients found naturally in various foods can stimulate the brain, thereby affecting data. Before the experiment, participants completed a questionnaire regarding their age, height, and weight. We also their measured body mass index (BMI) (ioi 353; Jawon Medical, Gyeongsan, South Korea). On completion of the study, participants received a $20 incentive. This study was approved by the Institutional Review Board of Konkuk University (7001355-2017-10-HR-206).

Experimental condition. The experiment environment was created in a space (180 cm × 160 cm) at the campus of Konkuk University in Seoul, South Korea. Ivory curtains were installed on both sides of the walls in front of the space, and white sheets were attached to the desks to minimize external stimuli during the experiment. The conditions of the experimental space were as follows: average temperature, 21.9 ± 3.4 °C; average relative humidity, 26.5 ± 10.2%; and average light intensity, 1184.7 ± 1094.5 lx.

Experimental procedure. This study had a crossover experimental design (Kim et al., 2020; Oh et al., 2019). Before commencing the experiment, the participants rested for 1 min on chairs in the experimental space. Then, the participants randomly performed nonhorticultural and horticultural activities for 3 min each. After each activity, a questionnaire was conducted to record the subjective emotions of the participants, followed by 1 min of rest. A total of nine activities were performed before the experiment was concluded (Fig. 1). The duration of the experiment per participant was ≈70 min.

The activities were divided into four horticultural activities and five nonhorticultural activities (Table 1). Horticultural activities included harvesting red lettuce (*Lactuca sativa* L.) planted in garden boxes (Fig. 2A). The planting activity involved transferring peperomia (*Peperomia argyreia*) to a pot (-Fig. 2B). The sowing activity involved sowing radish seeds (*Raphanus sativus* L.) in a sowing tray (Fig. 2C). Finally, the soil-mixing activity involved mixing horticultural soil (Fig. 2D).

In nonhorticultural activities, the ball-play activity involved bouncing a basketball in the experimental space (Fig. 2E). During the math activity, participants solved arithmetic problems excerpted from Korean national textbooks (Choi, 2015, 2017; Kang and Choi, 2015, 2017) appropriate for their grades (Fig. 2F). The video activity involved watching an animated television show called "Pokemon" (Fig. 2G). Before the paper-folding activity, the participants were taught to fold a paper airplane before the experiment. During the experiment, they were instructed to fold the paper in the manner in which they were taught (Fig. 2H). The reading activity involved reading Korean fairytales in an elementary school textbook (Fig. 2I).

Measurement. A wireless dry EEG device (Quick-20; Cognionics, San Diego, CA) was used to measure the participants' brain waves during both nonhorticultural and horticultural activities. This device minimizes the risk of electric shock compared to the wet electrode systems using electrolyte gel. Data were collected by amplifying and processing electrical signals measured via dry electrodes applied to the scalp. This device has been safety certified by the European Commission and the Federal Communications Commission (Kim et al., 2020).

The electrode application adhered to the international 10- to 20-electrode arrangement system (Jasper, 1958). The reference electrode was attached to the left earlobe (A1). The EEG results were measured using channels of the left prefrontal lobe (Fp1) and right prefrontal lobe (Fp2) involved in cognitive function (Fig. 3) (Miller and Cohen, 2001).

The SDM was used to evaluate the participants' psychological responses to each activity. SDM was developed by Osgood et al. (1957) to measure emotions using adjectives. The SDM is rated using a 13-point Likert scale and comprises three items: "comfortable–uncomfortable," "natural–artificial," and "relaxed–awakening." The higher the score, the more positive the emotional state.

Data analysis. The EEG data were analyzed using Cognionics Data Acquisition (Cognionics). Brain waves from the cerebral cortex were classified as theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (30–50 Hz) waves according to the frequency band (Sowndhararajan et al., 2015). The activation of each frequency band can be interpreted as having different meanings. For example, theta waves indicate shallow sleep, alpha waves refer to a stable condition, beta waves signify brain activity, and gamma waves show anxiety or excitement (Kim and Choi, 2001). This study analyzed the RT power spectrum, RMB power spectrum, and RSMT. The RT power spectrum was obtained by dividing the theta wave (4–8 Hz) by the total frequency (4–50 Hz). The RMB power spectrum was obtained by dividing the mid beta wave (15–20 Hz) by the total frequency (4–50 Hz). Finally, the RSMT was obtained by dividing the SMR to mid beta (12–20 Hz) by the theta wave (4–8 Hz) (Sowndhararajan et al., 2015).

The results of the EEG and SDM for each activity were analyzed using IBM SPSS Statistics for Windows (version 25; IBM Corp., Armonk, NY). A one-way analysis of variance and Duncan's multiple range tests were used as the analysis methods, and the significance level was set at $P < 0.05$. To analyze demographic information, Microsoft Excel (Microsoft Office 365 ProPlus; Microsoft, Redmond, WA) was used to determine the descriptive statistics.

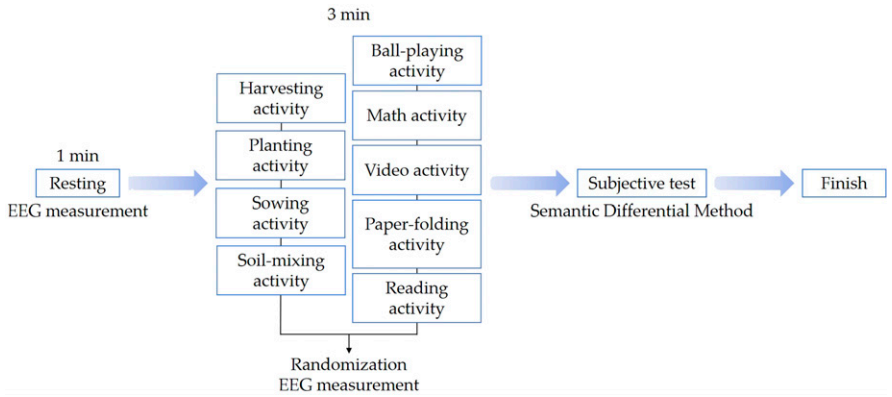


Fig. 1. Experimental protocol. EEG, electroencephalography.

Table 1. Description of activities.

Division	Activity	Descriptions
Horticultural activities	Harvesting	Harvesting red lettuce (*Lactuca sativa* L.) from a garden box (100 cm × 39 cm × 39 cm)
	Planting	Plating peperomia (*Peperomia argyreia*) in a 10-cm pot
	Sowing	Planting radish (*Raphanus sativus* L.) seeds in a seed tray
	Soil-mixing	Using hands to mix soil in the basin
Nonhorticultural activities	Ball-playing	Playing ball space (171 cm × 171 cm). Bouncing basketball.
	Math	Solving math problems appropriate for each grade (e.g., 392 × 47; 14 + 2 × 13 – 86; 18 × 5 ÷ 6; and 32 ÷ 11)
	Video	Watching the animated television show "Pokemon: Catch the carp king!"
	Paper-folding	Following the instructions for folding a paper airplane and then folding another paper airplane
	Reading	Reading fairy tale books



Fig. 2. Experimental performance appearance: (**A**) harvesting, (**B**) planting, (**C**) sowing, (**D**) soil-mixing, (**E**) ball-play, (**F**) math, (**G**) watching a video, (**H**) paper-folding, and (**I**) reading activities.

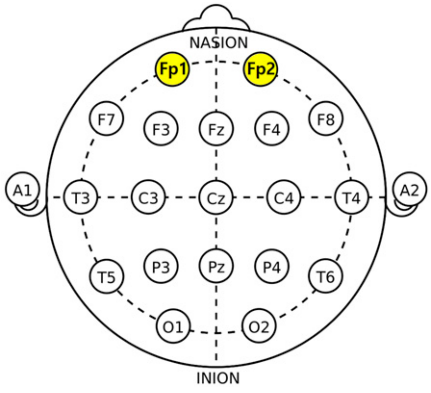


Fig. 3. Electrode locations of the international 10–20 system for electroencephalography (EEG).

Table 2. Descriptive characteristics of participants.

Variables	
Gender	% (N)
Male	36.7 (11)
Female	63.3 (19)
	Mean ± SD
Age (n = 30)	11.3 ± 1.3
[z]Weight (kg) (n = 29)	39.8 ± 11.3
[y]Height (cm) (n = 29)	143.8 ± 10.9
[x]Body mass index (kg·m^{-2}) (n = 29)	18.9 ± 3.3

[z]Body weight was measured using a body fat analyzer (ioi 353; Jawon Medical, South Korea).
[y]Height was measured using an anthropometer (Ok7979; Samhwa, Seoul, South Korea) without shoes.
[x]Body mass index was calculated using the formula, [weight (kg)]/[height (m)^2].

Results

Demographic characteristics. There were 30 participants (11 males and 19 females). The average age was 11.3 ± 1.3 years. The average weight was 39.8 ± 11.3 kg. The average height was 143.8 ± 10.9 cm. The average BMI was 18.9 ± 3.3 kg·m^{-2}, which is within the normal range based on the standards of the Korea Centers for Disease Control and Prevention (Table 2).

EEG. When performing the harvesting, video, and reading activities, the participants' RT power spectrum decreased in both prefrontal lobes ($P < 0.05$) (Table 3). Because the theta power is the reverse for attention skills, this result indicated that the participants' concentration increased (Han and Hong, 2017). Moreover, the participants' RMB power spectrum increased in the right prefrontal lobes when performing the harvesting and ball-play activities. The increase in the RMB power spectrum index signified the activity of the brain. Therefore, this result showed that there was brain activation in participants when performing the harvesting and ball-play activities. The RSMT analysis showed that activity was significantly higher in the right prefrontal lobes of the children when performing the harvesting activity than during other activities. The RSMT was calculated as the beta wave and theta wave, which are indicators of concentration and attention ability (Lubar, 1991; Lubar et al.,

Table 3. Results of the relative theta (RT) power spectrum, relative mid beta (RMB) power spectrum, and ratio of sensorimotor rhythm (SMR) from mid beta to theta (RSMT) according to electroencephalography (EEG).

		RT[z]		RMB[y]		RSMT[x]	
		Fp1	Fp2	Fp1	Fp2	Fp1	Fp2
EEG	Activity	Mean ± SD					
Total (N = 30)	Harvesting	0.27 ± 0.08 b[v]	0.27 ± 0.08 b	0.09 ± 0.02 ab	0.10 ± 0.04 a	0.66 ± 0.28	0.86 ± 1.10 a
	Planting	0.31 ± 0.08 ab	0.31 ± 0.08 ab	0.09 ± 0.01 b	0.09 ± 0.01 b	0.53 ± 0.18	0.54 ± 0.19 b
	Sowing	0.30 ± 0.08 ab	0.30 ± 0.09 ab	0.09 ± 0.02 b	0.09 ± 0.01 b	0.57 ± 0.25	0.54 ± 0.18 b
	Soil-mixing	0.31 ± 0.08 ab	0.30 ± 0.07 ab	0.09 ± 0.01 b	0.09 ± 0.01 ab	0.54 ± 0.16	0.56 ± 0.15 b
	Ball-playing	0.33 ± 0.09 a	0.33 ± 0.08 a	0.10 ± 0.03 a	0.10 ± 0.02 a	0.66 ± 0.39	0.58 ± 0.19 b
	Math	0.33 ± 0.08 a	0.31 ± 0.07 ab	0.09 ± 0.02 b	0.09 ± 0.01 b	0.53 ± 0.21	0.53 ± 0.16 b
	Video	0.28 ± 0.08 b	0.29 ± 0.07 b	0.09 ± 0.02 ab	0.09 ± 0.01 b	0.64 ± 0.32	0.56 ± 0.14 b
	Paper-folding	0.31 ± 0.09 ab	0.30 ± 0.07 ab	0.08 ± 0.01 b	0.09 ± 0.01 b	0.52 ± 0.13	0.54 ± 0.13 b
	Reading	0.27 ± 0.07 b	0.27 ± 0.07 b	0.09 ± 0.01 b	0.09 ± 0.01 b	0.60 ± 0.15	0.59 ± 0.16 b
	P[w]	0.026*	0.016*	0.006*	0.015*	0.100[NS]	0.042*

[z]RT power spectrum was calculated by [theta (4–8 Hz) power] / [total frequency (4–50 Hz) power].
[y]RMB power spectrum was calculated by [mid beta (15–20 Hz) power] / [total frequency (4–50 Hz) power].
[x]RSMT was calculated by [SMR-mid beta (12–20 Hz) power] / [theta (4–8 Hz) power].
[w]Statistical significance as determined using a one-way analysis of variance.
[v]Statistical significance as determined using Duncan's multiple range tests.
Fp1 = left prefrontal lobe; Fp2 = right prefrontal lobe.
Post hoc analysis: a > b according to Duncan's multiple range tests.
NS, *Nonsignificant or significant at $P < 0.05$, respectively.

1995). Therefore, the harvesting activity effectively improved the brain activity and concentration of participants.

Subjective emotion assessment. The results of the SDM survey showed that participants felt more positive when performing horticultural activities than when performing nonhorticultural activities. There was no significant difference in the "being comfortable" item scores, although engaging in horticultural activities led to higher scores than engaging in non-horticultural activities (Fig. 4A). The "being natural" item scores were significantly higher when performing horticultural activities rather than when performing nonhorticultural activities (Fig. 4B), and the "being relaxed" item scores were significantly higher when performing horticultural and reading activities when compared with the other activities (Fig. 4C).

Discussion

We investigated the effects of horticultural activities and compared them with those of nonhorticultural activities on children by measuring psycho-physiological aspects, such as the EEG and subjective mood conditions. The results showed that during the harvesting activity, the RT power spectrum in the prefrontal lobes of the children significantly decreased, and that the RMB power spectrum and RSMT in the right prefrontal lobe increased significantly compared with other activities. In addition, the SDM results showed that children experienced more psychological stability when performing horticultural activities compared to nonhorticultural activities.

During the harvesting activity, the RT power spectrum index of the participants was significantly decreased and the RMB power spectrum and RSMT indexes were significantly increased in the prefrontal lobes compared to those during other activities (Table 3). The ratio of theta waves and beta waves is related to concentration; furthermore, these waves are subsequently related to mental activity, problem-solving, and decision-making (Sauseng and Klimesch, 2008). They occur naturally during intensive activities, such as deep conversation, sports, and speeches (Hassan et al., 2018a). Therefore, the RSMT and RMB power spectrum indexes are indicators of concentration; therefore, they indicate increased concentration as the theta waves decrease and beta waves increase (Lubar, 1991). An excessively high frequency of theta waves indicates a low level of attention and brain activity (Clarke et al., 2002). For children with attention deficit hyperactivity disorder (ADHD), theta waves are higher than usual (Lazzaro et al., 2001). Lubar (1991) presented the ratio of beta and theta waves as a measure of distinguishing children with and without ADHD. Children with ADHD exhibit increased theta waves in the frontal lobe and decreased frequency of beta waves (Chabot and Serfontein, 1996). Therefore, the increase in the RSMT and RMB power spectrum indexes and the decrease of the RT power spectrum index in the prefrontal lobes during harvesting activity indicated that concentration had improved. This is because children focused on harvesting lettuce during harvesting activities by looking at the color and size of lettuce in the garden, selecting lettuce to be harvested, being careful not to injure other lettuces, and grasping the bottom of the leaf stem to harvest lettuce. In a previous study, Kim et al. (2020) also reported that children's brain activity and attention skills were significantly increased when performing tasks in spaces with plants than in spaces without plants. Igarashi et al. (2015) reported that the prefrontal lobes of participants were activated when observing plants. In addition, Lee et al. (2018b) reported that the RSMT and RMB power spectrum indexes increased after adults engaged in plant-based activities. In this study, we measured and recorded brain waves in the prefrontal lobes of children. The prefrontal lobe is the fastest developing area of a child's brain (Arden and Linford, 2008). Furthermore, the prefrontal lobe is responsible for creativity during cognitive processes and plays a key role in attention, working memory, and goal-oriented behavior (Fuster, 2002). It has also been found to help organize experiences over time (Knight and Grabowecky, 1995). Therefore, it can be said that the frontal lobe is related to cognitive function (Burgess et al., 2007; Sakai and Passingham, 2003).

The brain can be divided into left and right hemispheres. The left hemisphere has linguistic functions and is analytical, slow, and methodical during the processing of single information. The right hemisphere oversees nonverbal functions and is associated with parallel information processing (Cohen, 1973; Xiong et al., 1998). In this study, the results of the EEG during the harvesting activity showed that the RMB power spectrum and RSMT indexes were activated in the right brain hemisphere. This is consistent with previous research that indicated that the right hemisphere is activated in environments with plants and during activities involving plants (Kim et al., 2020; Lee et al., 2018b).

The SDM survey results showed that the items indicating feelings of "being natural" and "being relaxed" had significantly higher scores when performing horticultural activities. This is consistent with a previous study that showed that children exhibited positive emotional states when looking at foliage plants (Oh et al., 2019). Similarly, adults also reported feeling calmer and more comfortable when engaging in plant-based activities (Hassan et al., 2018b). Working with plants has been shown to reduce anxiety (Hassan et al., 2019). Tao et al. (2020) reported that the anxiety index of adults decreased when performing horticultural activities compared with that when performing computer tasks. Shao et al. (2020) compared engagement in horticultural activities and smartphone games performed by children and reported that the parasympathetic nerves increased during horticultural activities. Additionally, skin conductance and sympathetic nerves decreased, thereby reducing tension and stress (Shao et al., 2020).

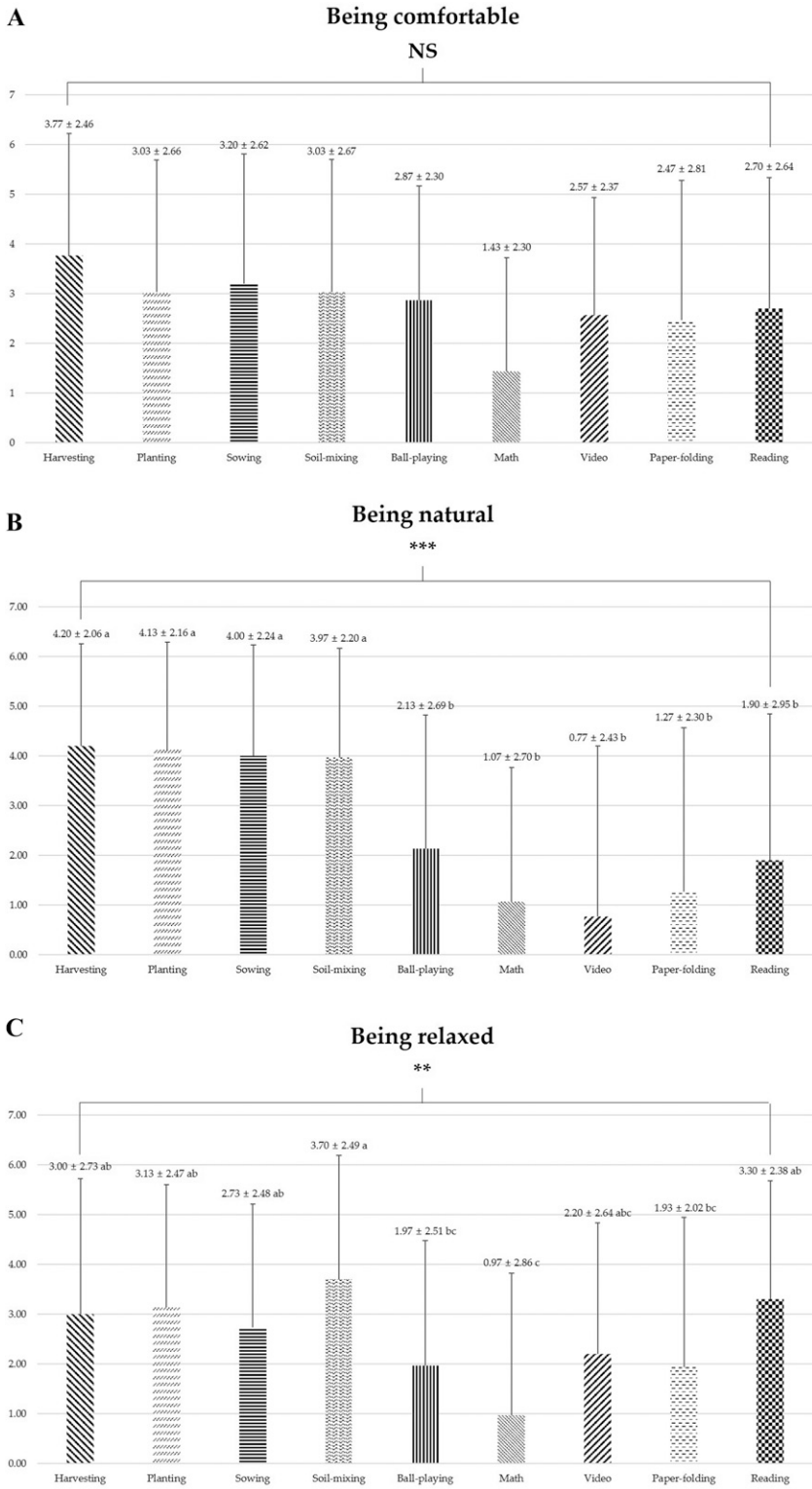


Fig. 4. Comparisons of a semantic differential method (SDM) for each activity. Data are presented as means ± SD (N = 30). (**A**) Being comfortable. (**B**) Being natural. (**C**) Being relaxed. NS, nonsignificant. $^{**}P < 0.01$ and $^{***}P < 0.001$ according to the one-way analysis of variance. Post hoc analysis: a > b > c according to Duncan's multiple range tests.

In conclusion, this study revealed that horticultural activities can increase the concentration in children and stabilize their emotional state. Particularly, the harvesting activity was most effective for improving children's brain activity and concentration. The results of this study can be used as baseline data and scientific evidence when developing a horticultural therapy program to improve the concentration and emotional stability of children. It is difficult to generalize the results of this study because of the small sample size. Therefore, further studies should increase the number of participants and analyze specific physiological mechanisms, including comparisons between gender and age. It would be interesting to compare the physiological responses of adults with children in future studies. Because this study was conducted in a controlled indoor experimental space, further studies involving psycho-physiological measurements and comparing the effects of horticultural activities in natural spaces are necessary.

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ENVIRONMENTAL STUDIES

Biodiversity intervention enhances immune regulation and health-associated commensal microbiota among daycare children

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As the incidence of immune-mediated diseases has increased rapidly in developed societies, there is an unmet need for novel prophylactic practices to fight against these maladies. This study is the first human intervention trial in which urban environmental biodiversity was manipulated to examine its effects on the commensal microbiome and immunoregulation in children. We analyzed changes in the skin and gut microbiota and blood immune markers of children during a 28-day biodiversity intervention. Children in standard urban and nature-oriented daycare centers were analyzed for comparison. The intervention diversified both the environmental and skin Gammaproteobacterial communities, which, in turn, were associated with increases in plasma TGF-β1 levels and the proportion of regulatory T cells. The plasma IL-10:IL-17A ratio increased among intervention children during the trial. Our findings suggest that biodiversity intervention enhances immunoregulatory pathways and provide an incentive for future prophylactic approaches to reduce the risk of immune-mediated diseases in urban societies.

INTRODUCTION

Observational studies have demonstrated that immune-mediated diseases are more frequent in populations adopting modern urban lifestyles than in populations with a preindustrial lifestyle (*1*–*3*). One of the leading hypotheses argues that the core reason for this pattern is the evident biodiversity loss in modern living environments (*3*–*6*). However, conclusive evidence based on human intervention trials is still lacking.

Biodiversity loss in urban areas limits exposure to diverse microbiota but increases exposure to pathogenic bacteria in densely built areas (*5*). High hygiene level and Western urban lifestyle (e.g., consumption of processed food and use of antibiotics) also influence the human commensal microbiota (*7*, *8*). Furthermore, urban pollutants alter microbial communities associated with human health and immune-mediated diseases (*9*–*11*). All of these factors may result in microbial imbalance, referred to as dysbiosis, which has been associated with immune-mediated diseases (*4*, *12*, *13*).

Early life determinants of gut microbiota include birth mode, genetics, use of antibiotics, diet, and other environmental factors (*14*). Whereas the gut microbiota of 1-year-old children are dominated by *Faecalibacterium*, *Bacteroides*, and *Anaerostipes* (*15*), healthy adult gut microbiota are characterized by the phyla Bacteroidetes and Firmicutes, particularly the genera *Bacteroides* and *Prevotella* (*16*, *17*). Lactobacillales is the dominant order on the skin of 1-year-old children, and the diversity of the skin microbiota increases with age (*18*). Core reasons why skin microbiota changes with age are related to human physiology and increased influence of external factors, such as pets and living environment (*18*). The dominant bacterial taxa on the skin of healthy adults are characterized by the phyla Actinobacteria, Firmicutes, and Proteobacteria, particularly the genera *Propionibacterium*, *Staphylococcus*, and *Corynebacterium* (*16*, *19*). Actinobacteria and Proteobacteria are also dominant phyla in soil (*5*, *6*, *10*, *11*). While skin and soil bacterial communities contain several taxa in common (*4*, *19*, *20*), bacterial taxonomies differ noticeably between soil and gut communities (*5*, *17*, *21*). Despite this taxonomic divergence, recent findings indicate that the type of ground cover and garden vegetation around permanent residences have an impact on gut microflora (*17*).

Environmental microbial exposure, human commensal microbiota, and immunological pathways are generally assumed to be interconnected (*4*, *8*, *14*, *17*). Plasma cytokine levels and blood FOXP3$^+$ regulatory T (T_{reg}) cell frequencies can be used as surrogates for changes in immunoregulatory pathways. Interleukin-10 (IL-10) is an anti-inflammatory cytokine, and its blood levels reflect the activation of immunoregulatory pathways (*22*). Transforming growth factor–β1 (TGF-β1) is a multifunctional cytokine that down-regulates inflammatory processes, particularly in the gut-associated immune system (*22*). IL-17 is a proinflammatory cytokine that is associated with several immune-mediated diseases, including type 1 diabetes (*23*), inflammatory bowel disease, rheumatoid arthritis, and multiple sclerosis (*24*). T_{reg} cells are essential regulators of immune system, with important roles in maintaining self-tolerance as well as tolerance to commensal microbiota, thus preventing autoimmune and chronic inflammatory diseases (*25*).

As immune-mediated diseases are an emerging health issue in urbanized societies, there is an unmet need for novel prophylactic

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practices to combat these maladies. To address this need, we performed an intervention study to test the biodiversity hypothesis (*3*). In this study, the environmental biodiversity of urban daycare centers was enriched by covering their yards with forest floor and sod. The effect of the intervention was studied among 75 urban children aged 3 to 5 years residing in three different daycare environments: (i) standard yards, (ii) intervention yards with biodiversity elements, and (iii) nature-oriented daycare centers where children visited nearby forests on a daily basis. We measured skin and gut microbiota, plasma cytokine levels, and blood T_{reg} frequencies in these children before and after the 28-day intervention period. Moreover, we compared environmental microbiota between the standard and intervention daycare yards. On the basis of earlier comparative studies among children (*1*, *4*), we hypothesized that the biodiversity intervention will affect the commensal microbiota of the children and that a positive change in skin microbial diversity would be associated with enhanced secretion of immunoregulatory cytokines and/or increase in T_{reg} cells after the trial. In addition, we expected the changes in commensal microbiota to reflect the composition of environmental microbiota in the intervention group and associations between the commensal microbiota and immune response to be different in this group compared to the standard daycare group.

RESULTS

Intervention modified surface soil microbiota in daycare yards

Ten daycare centers in two cities in Finland (Lahti and Tampere), both having populations of more than 100,000 inhabitants, were included in the study (Table 1). Three of these were nature-oriented daycare centers that served as a positive control (study subjects, $n = 23$). Each of standard urban daycare centers contained approximately 500-m^2 yards with little or no green space. In four of these daycare yards, called "intervention daycares" hereafter, we covered part of the gravel with forest floor (100 m^2) and sod (200 m^2) (study subjects, $n = 36$). The three nonmodified yards ("standard daycares") served as controls (study subjects, $n = 16$). Intervention daycares received segments of forest floor, sod, planters for growing annuals, and peat blocks for climbing and digging.

Vegetation in the transferred natural forest floor consisted mainly of dwarf heather (*Calluna vulgaris*), blueberries (*Vaccinium* sp.), crowberry (*Empetrum nigrum*), and mosses (*Pleurozium shreberi*, *Hylocomium splendens*, *Sphagnum* sp., and *Dicranum* sp.). The sod consisted of fescues (*Festuca* sp.) and meadow grasses (*Poa* sp.). Nurses of the daycare centers guided children to be in contact with the green materials brought into the yard. Guided activities included, for example, planting plants in planting boxes, crafting natural materials, and playing games. In addition, green materials were available to children during free outdoor activities (*26*). Children played in the yards approximately 0.5 to 2 hours twice a day in intervention and standard daycare centers (*26*). The average time outdoors was 1.5 hours.

Children were served three uniform meals daily (breakfast, lunch, and afternoon snack) in the participating daycare centers; two central kitchens, one per city, prepared the meals according to detailed guidelines for early childhood, published by Finnish food authority National Nutrition Council (www.ruokavirasto.fi/en/themes/healthy-diet/national-nutrition-council/). Private consumption of fresh plants, number of animal contacts, time spent outdoors or in nature, and number of siblings were similar among all daycare groups (table S1). The intervention lasted for 28 days in May to June 2016.

To measure differences in the environmental microbial community between modified and nonmodified daycare yards and to estimate whether the taxonomic changes were similar to those in skin bacterial communities, we compared community composition, relative abundances, richness, and diversity of bacterial communities in surface soil samples. We sampled surface soil from intervention and standard daycare yards after the intervention period of 28 days (samples collected from the sandbox and playground, next to swing, jungle gym, and the main door). The same surface soils (sandbox and playground) were sampled also on day 0 before the intervention materials arrived.

In surface soil samples, the relative abundances of Proteobacteria (36% before and 34% after intervention), Bacteroidetes (24 and 28%), Actinobacteria (20 and 15%), and Acidobacteria (5 and 7%) were above 5%. After the intervention, the community compositions of these phyla and the total bacterial community differed between intervention and standard daycare yards (table S2A and fig. S1A). The

Table 1. Number, age, gender, and reasons for exclusion of study participants in each daycare group and in total. Each child spent daily (Monday to Friday) approximately 1.5 hours outdoors.

	Intervention* 4 centers	Standard† 3 centers	Nature‡ 3 centers	Total children 10 centers
Total children	36	16	23	75
Boys	18	9	10	37
Girls	18	7	13	38
Age§	4.3 ± 0.6	4.9 ± 0.3	4.7 ± 0.5	4.6 ± 0.6
Excluded‖				
Antibiotic users	2	1	0	3
Probiotic users	1	0	1	2
Medication users	3	2	3	8

*Children in intervention daycare centers. †Children in standard, nonmodified daycare centers. ‡Children in nature-oriented daycare centers where children visited boreal forests on a daily basis. §Age is presented as means ± SD. ‖Children using probiotics, antibiotics, or medication (paracetamol, desloratadine, pyrvin, cetirizine, and salbutamol) were excluded from the gut microbiome and cytokine analyses. One child with pinworm infection was excluded from all analyses.

intervention modified the community composition of Gamma proteobacteria in surface soils [abundance data in table S2B: permutational multivariate analysis of covariance (PERMANOVA), $P = 0.008$ and $P_{adj} = 0.03$; fig. S1B], and this community differed between the intervention and standard yards after the intervention (presence/absence data in table S2A: PERMANOVA, $P = 0.03$ and $P_{adj} = 0.05$; fig. S1B). Moreover, unclassified Gammaproteobacterial operational taxonomic units (OTUs) were enriched at intervention daycare yards, and their relative abundance was over eight times higher compared to standard daycare yards after the intervention period (table S3, A and B). Observed OTU richness and Shannon diversity of the total bacterial community ($P_{adj} = 0.04$ in both cases) and the richness of Gammaproteobacteria were higher in the intervention yards than in standard yards (Fig. 1, A and B, and table S3C). We used multivariate homogeneity of group dispersions [permutational analysis of multivariate dispersions (PERMDISP)] to examine beta diversity, and it showed that the beta diversity of five genera was higher in intervention than in standard daycare yards (table S2C).

Intervention promoted skin bacterial diversity

Consistent with previous studies (*4*, *12*), the biodiversity intervention was associated with high diversity of skin Proteobacteria. We compared skin bacterial Shannon diversity indexes between three different daycare groups with analysis of covariance (ANCOVA) and with Kruskal-Wallis and Dunn's multiple comparison post hoc tests using gender as a covariate. Before the intervention, children in nature-oriented daycares had divergent community composition of bacteria on skin compared to children in standard daycares (table S2D and fig. S1C) and more diverse Alphaproteobacterial skin community compared to intervention daycare children (Fig. 1D and table S4). Standard and intervention daycare groups had similar bacterial community composition (table S2D) and hosted equally diverse skin Proteobacterial communities, including classes of Alpha-, Beta-, and Gammaproteobacteria before the intervention period (Fig. 1, C to F, and table S4). After the trial, children in intervention daycares had more diverse skin Proteobacterial and Gammaproteobacterial communities than children in standard daycares (Fig. 1, C to F, and table S4). Before-after comparisons using paired *t* tests and Wilcox statistics resulted in a single difference: Alphaproteobacterial diversity increased in intervention daycares (Fig. 1D and table S5), being higher compared to children in standard daycares (Fig. 1D and table S4). These results demonstrate how the biodiversity intervention promoted or prevented the loss of skin bacterial diversity during the study period, leading to diversities comparable to those in nature-oriented daycares (Fig. 1).

Intervention modified gut bacterial community

Because probiotics and medications, such as antibiotics, are known to affect the gut microbial community (*14*, *27*), we excluded from the gut microbial analyses those study subjects receiving probiotics or medication during the intervention (Table 1). We observed several differences associated with the daycare environment. Among children in intervention daycare centers, the relative abundance of Clostridiales decreased ($P = 0.003$ and $P_{adj} = 0.04$), and the alpha diversity of Ruminococcaceae ($P = 0.01$ and $P_{adj} = 0.05$), known to contain butyrate-producing species, increased (table S6A; paired *t* tests). No such changes were seen in children in nature-oriented or standard daycares (table S6, B and C). We additionally compared differences in community composition of gut bacteria among the three daycare groups with PERMANOVA. Children in standard and nature-oriented daycares had dissimilar community composition of Ruminococcaceae both before ($P = 0.05$ and $P_{adj} = 0.10$) and after ($P = 0.01$ and $P_{adj} = 0.03$) the intervention period, while standard and intervention daycare children had similar communities of Ruminococcaceae at the beginning of the intervention ($P = 0.14$), but slightly divergent communities at the end of the intervention ($P = 0.03$ and $P_{adj} = 0.08$; table S2E and fig. S1, E and F). Moreover, *Faecalibacterium* taxa differed in PERMANOVA between nature-oriented and standard daycare children after the intervention ($P = 0.03$; table S2F).

Microbiota-immunological correlations

We analyzed the levels of cytokines IL-10, IL-17A, and TGF-β1 in plasma samples, and the frequency of $CD4^+CD25^+CD127^{low}FOXP3^+$ T_{reg} cells in blood samples by flow cytometry. We searched for associations between changes in plasma cytokine levels or total T_{reg} cell frequencies and changes in bacterial diversity and abundance with linear mixed-effects models (LMMs) and with nonmetric multidimensional scaling (NMDS). In addition, we performed a before-after comparison of the cytokine levels and their ratios. These comparisons demonstrated that the IL-10:IL-17A ratio increased among intervention children, but not among children in standard or nature daycares (Table 2).

When all children were analyzed together in an LMM, an increase in skin Gammaproteobacterial diversity was associated with an increase in TGF-β1 plasma concentration ($P_{adj} = 0.01$; Fig. 2A and table S7A), and among intervention children, this diversity increase was also associated with a decrease in IL-17A plasma level ($P_{adj} = 0.002$; Fig. 2B and table S7B) and increase in the percentage of T_{reg} cells ($P = 0.016$; Fig. 2C and table S7C). Among nature-oriented daycare children, high Gammaproteobacterial diversity in skin microbiomes was associated with an increase in IL-10 plasma concentration ($P_{adj} = 2.3 \times 10^{-6}$; table S7D), whereas among standard daycare children, low Gammaproteobacterial diversity was associated with a decrease in TGF-β1 expression ($P_{adj} = 0.01$; table S7E and fig. S2).

When all children were analyzed together in an NMDS model, the community composition of *Faecalibacterium* species in the gut was associated with plasma IL-17A concentration after the intervention period ($P = 0.015$ and $P_{adj} = 0.045$; table S8). Within nature-oriented children, the higher abundance of *Faecalibacterium* Otu00007 (*Faecalibacterium prausnitzii* in BLASTN; query cover = 100%, *E* value = 2×10^{-127}, ident = 99%) was associated with lower levels of IL-17A in plasma (LMM, $P_{adj} = 0.004$), whereas a higher abundance of *Faecalibacterium* Otu000008 (no match in BLASTN with the significance threshold of 10) was associated with higher levels of IL-17A in plasma (LMM, $P_{adj} = 0.009$; Fig. 2D and table S7F). The latter association was weaker but significant also among children in standard daycares (LMM, $P_{adj} = 0.04$; table S7G). Among nature-oriented daycare children, the decrease in plasma IL-17A concentration was additionally associated with a decrease in the relative abundance of *Romboutsia* ($P_{adj} = 5.7 \times 10^{-5}$) and *Dorea* ($P_{adj} = 0.03$) and an increase in *Anaerostipes* ($P_{adj} = 0.01$) in the gut (table S7H).

DISCUSSION

While early exposure to environmental biodiversity has been linked to the development of a well-functioning immune system (*1*, *4*), the final proof of causality is still lacking. This study is the first human

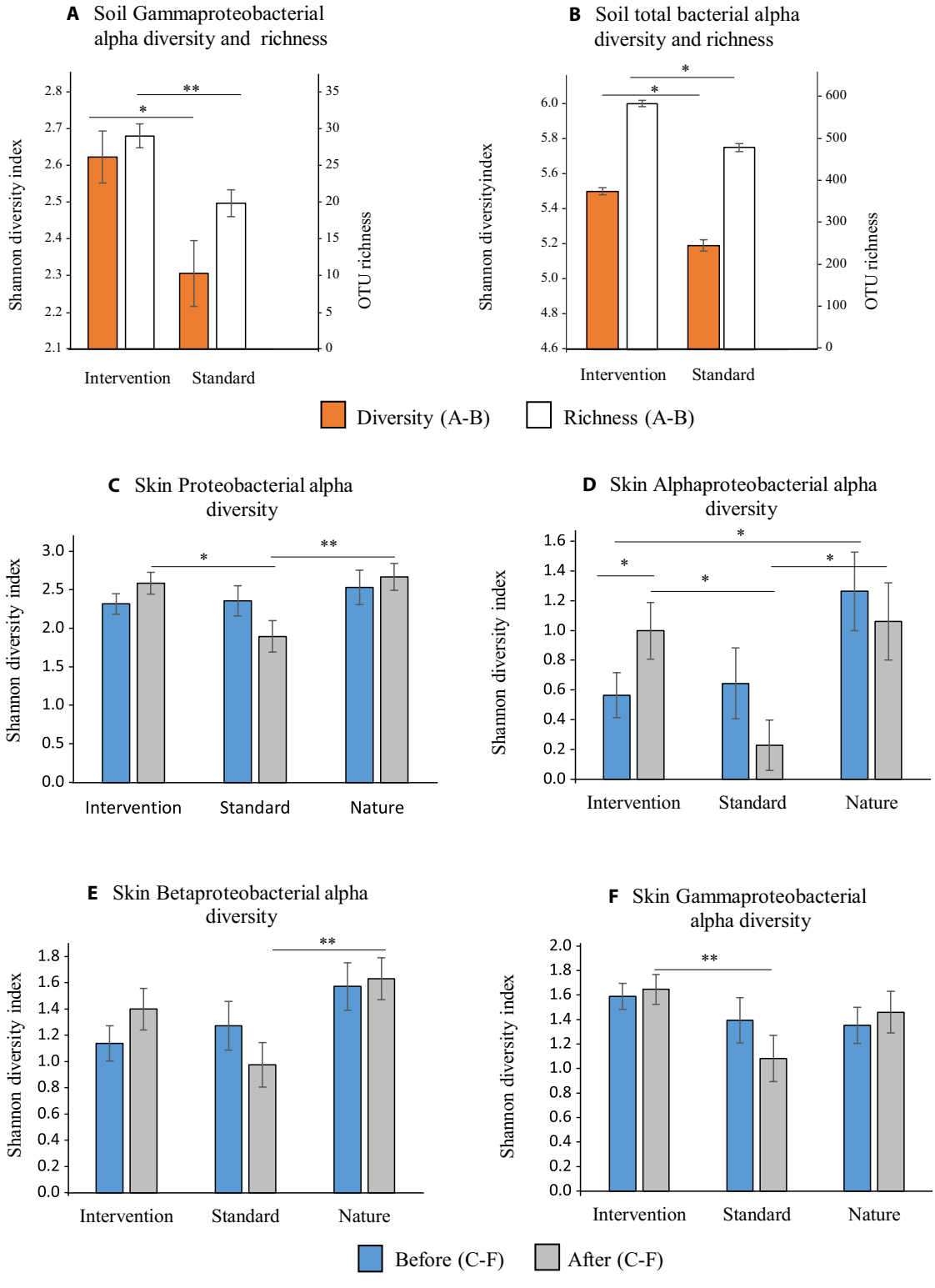


Fig. 1. Diversity and richness of bacteria in daycare yard soils and on the skin of daycare children. After the trial, (**A**) Gammaproteobacterial and (**B**) total bacterial ground surface soil community was more diverse at intervention daycare yard soils compared to standard daycare yards. On the skin, the alpha diversity (Shannon index) of (**C**) Proteobacteria was higher among children in intervention ($n = 29$) and nature-oriented daycares ($n = 19$) compared to children in standard daycares ($n = 13$) after the study period. (**D**) Alphaproteobacterial diversity on the skin of the intervention daycare children increased during the intervention, and it was higher compared to children in standard daycares after the study period. (**E**) Betaproteobacterial diversity was higher among nature-oriented and (**F**) Gammaproteobacterial diversity higher among intervention daycare children compared to children in standard daycares after the study period. Data are displayed as means ± SE. $^*P < 0.05$ and $^{**}P < 0.01$, *t* tests after the intervention (A and B), Dunn's multiple comparison post hoc tests after the intervention (C to E), and Wilcoxon signed-rank test (D).

Table 2. IL-10:IL-17A ratio before and after (mean ± SD) the 28-day intervention period in plasma of children in the intervention, standard, and nature daycares.

Daycare center	Mean before	SD	Mean after	SD	df*	*P*	Adjusted $P^{\dagger}$, Wilcoxon paired test
Intervention	0.86	0.50	1.15	0.10	21	**0.02**‡	**0.04**‡
Standard	0.93	0.47	1.04	0.44	9	0.81	1
Nature	1.22	0.92	0.96	0.55	9	0.29	0.86

*Degree of freedom. Only donors with both before and after samples were included. †Benjamini-Hochberg correction. ‡Significant differences are indicated in boldface.

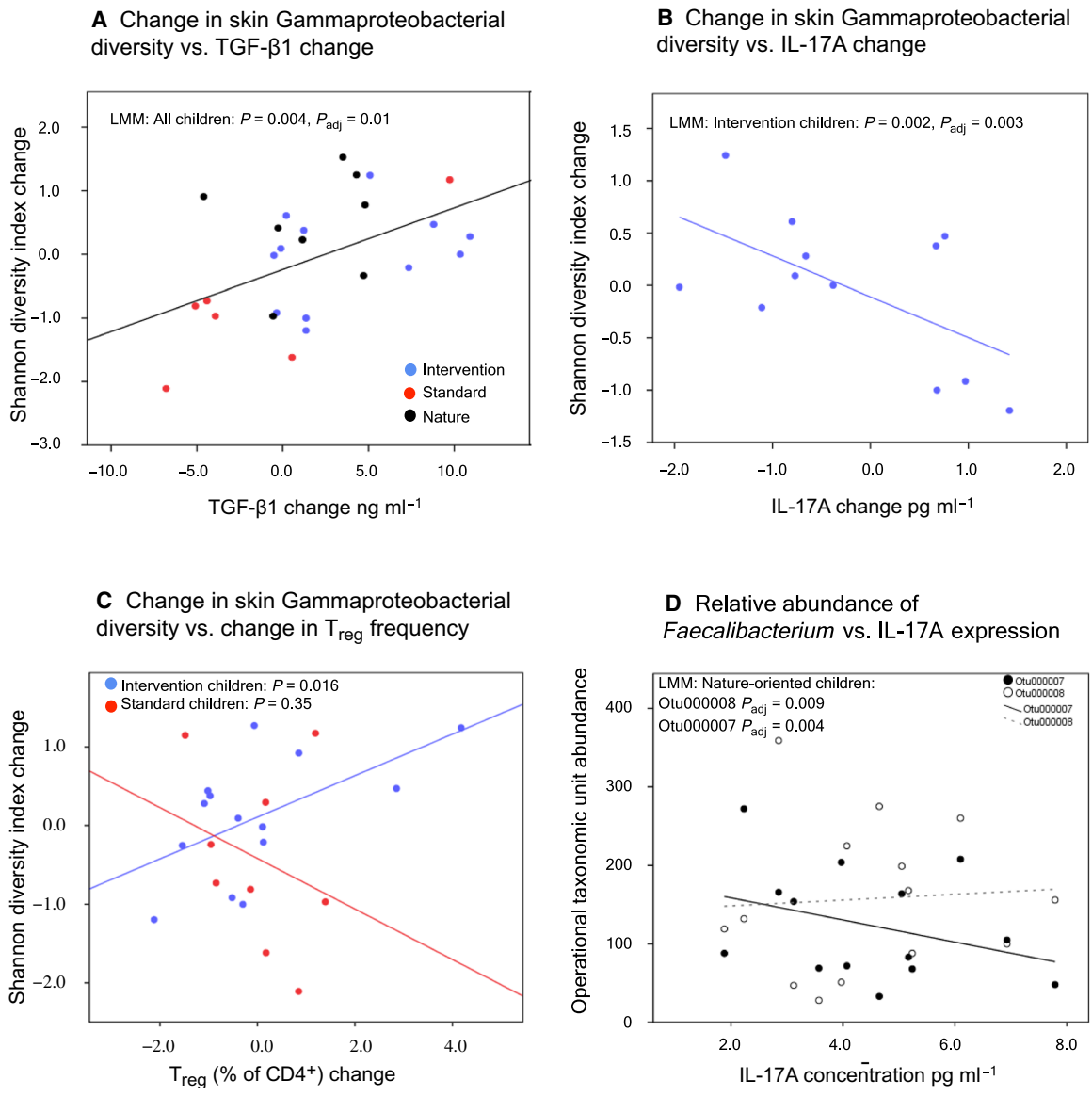


Fig. 2. Associations between bacterial diversity and immune markers. The increase in skin Gammaproteobacterial diversity was associated (**A**) with an increase in TGF-β1 concentration in plasma (all children in an LMM) and among intervention children (**B**) with a decrease in IL-17A concentration (**C**) and increase in T_{reg} cell frequencies. In (C), the nonsignificant model for standard children is provided for comparison. (**D**) Among nature-oriented children, *F. prausnitzii* (Otu000007) was associated with a decrease and unknown *Faecalibacterium* Otu000008 with an increase in IL-17A concentration (results from end of trial).

intervention trial in which urban environmental biodiversity was manipulated to examine its effects on commensal microbiome and the immune system in young children. The 28-day-long intervention that included enrichment of daycare center yards for microbial biodiversity was associated with changes in the skin and gut microbiota of children, which, in turn, were related to changes in plasma cytokine levels and T_{reg} cell frequencies. These findings suggest that the exposure to environmental microbial diversity can change the microbiome and modulate the function of the immune system in children. Specifically, the intervention was associated with a shift toward a higher ratio between plasma cytokine IL-10 and IL-17A levels and a positive association between Gammaproteobacterial diversity and T_{reg} cell frequencies in blood, suggesting that the intervention may have stimulated immunoregulatory pathways. These regulatory changes occurred despite slightly inconsistent findings in skin microbiota (see Figs. 1 and 2). Overall, the study indicates that it may be possible to modulate the immune system by relatively simple actions that change the living environment of young children in urban communities.

The intervention maintained a high diversity of commensal skin microbiota, particularly among Gammaproteobacteria, relative to the children in standard daycares, in whom the diversity of these microbiota declined over the study period. Our results are in line with previous observational studies showing associations between immune system markers, living environment, and commensal microbiota, including skin Gammaproteobacteria (*1*, *4*, *12*). Thus, the results of the present intervention study support the biodiversity hypothesis (*3*, *4*). Because biodiversity intervention offers embodied experiences of nature and provides multisensory exploration and diverse learning situations (*26*), children might have more direct contacts with soil and vegetation in intervention than in standard daycares. Time spent in the yards might also be one explanation why the skin Proteobacterial diversities declined among children in standard daycares but not among children in intervention daycares, although time spent outdoors was similar in all daycare groups. Our conclusion is that letting urban children play in microbiologically diverse dirt and vegetation alters skin and gut microbiota, which is accompanied by parallel changes in the immune system within a relatively short period of 1 month.

An important aspect of these findings is that the commensal microbiota of children in intervention daycare centers became more similar to that observed in children attending nature-oriented daycares (Fig. 1), where children make daily visits to nearby forests. Today, a vast majority of children in developed societies, and increasing numbers in developing ones, live in urban areas (*28*), and many of them have limited access to areas characterized by rich natural biodiversity such as forests. In addition, green areas surrounding urban environments are often contaminated by pests and pathogenic microbes (*29*). For this reason, one can anticipate that providing children with a chance for daily contact with diverse vegetation and dirt in safe urban green spaces such as playgrounds and daycare center or schoolyards might improve child health by activating the regulatory pathways of the immune system. This could reduce overactive immune responses and, consequently, decrease the risk of developing immune-mediated diseases. In addition, biodiversity intervention may afford well-being benefits and increase children's physical activity (*26*). The findings of the present study and our previous well-being study (*26*) encourage implementation of these solutions in the management and planning of the urban environments.

Exposure to microbial biodiversity affected the gut microbiota, particularly Ruminococcaceae (including *Faecalibacterium*), which includes Gram-negative bacteria associated with the maintenance of gut health (*30*). The family also contains established or candidate probiotics (*13*). The intervention increased the diversity of Ruminococcaceae, although intervention materials per se did not contain the strains found in stool samples. This raises the question of whether the mechanism of immune regulation in the biodiversity intervention was fundamentally different from the impacts of probiotic treatments; probiotics improve the abundance of certain strains only and may even delay the recovery of gut microbiota after antibiotic treatments (*31*). Probiotic treatments have also shown only limited, if any, effect in the prevention of allergies (*32*). Moreover, our approach—biodiversity intervention—exposed children to a wide spectrum of environmental microbes, including microscopic invertebrates, protozoa, fungi, archaea, and viruses. This exposure also happened via multiple routes including skin and mucosal routes. Thus, this kind of biodiversity intervention should activate a much wider spectrum of pattern recognition receptors (PRRs) than oral treatment with probiotic bacteria (*33*). However, further studies will be needed to elucidate the nature of the potential wide-spectrum PRR stimulation by the presently described approach.

The decreasing diversity of skin microbiota in the standard non-intervention daycare group may also be explained by a decrease in microbial activity during the intervention period. As the intervention started less than a month after snow melt, and as the intervention period was dry, the top of mineral soil, concrete, and asphalt plausibly dried during the intervention. Hence, it is not unexpected that Gammaproteobacterial richness and the abundance of unidentified OTUs were higher in intervention than standard yards at the end of the intervention period (see Fig. 1 and table S3). As children in the intervention group were in daily contact with rich ground surface Gammaproteobacterial community on weekdays, and as Gammaproteobacteria position themselves below subepidermal compartments in the skin (*34*), their skin Gammaproteobacterial content plausibly maintained higher compared to children in standard daycares. Touching organic landscaping materials has been shown to immediately increase the diversity of Proteobacteria, including Gammaproteobacteria, on skin (*19*). A parallel factor was the increased willingness to play with soil and plant materials in the intervention yards (*26*), leading to increased voluntary microbial exposure by children.

Standard daycare yards consisting of mostly inorganic man-made landscaping materials can be considered as man-made harsh, arid environments. As arid environments typically host low microbial activity but huge microbial diversity particularly under nutrient depletion (*35*), we were surprised to see higher Proteobacterial richness in intervention yards. It is possible that parts of the Proteobacterial community in intervention yards originated from preintervention period and that the transfer of sod and forest floor resulted in a lag time during which bacterial diversity and richness were still adapting to the new growth-supporting environment. We recommend following the effects of biodiversity intervention over a longer period to understand the microbial community dynamics on daycare yards and to see the longevity of changes in plasma cytokines.

Factors shaping immune response include changes in the external environment and exposure to human pathogens. The latter induces a proinflammatory response, e.g., affects IL-10:IL-17A ratio (see Table 2). Because heterogeneous home environments did not

mask differences between daycare groups (see Fig. 1), the impact of the biodiversity intervention on commensal microbiota was strong compared to potential temporary exposures during the intervention period. As Gammaproteobacterial richness was improved and unidentified OTUs within Gammaproteobacteria were enriched at the intervention yards only, changes in skin Gammaproteobacteria in standard and nature-oriented groups were plausibly of different origin compared to the intervention group. This is not unexpected as in the standard group Gammaproteobacteria arrived from urban nongreen environment, and as children in nature-oriented daycare centers were exposed to forest biodiversity throughout the year. Therefore, and as we recently demonstrated how exposure to organic soil reduces the relative abundance of genera containing opportunistic pathogens on the skin of urban dwellers (*36*), the positive associations between skin Gammaproteobacterial diversity and plasma IL-17A levels in the nonintervention groups may be a consequence of exposure to Gammaproteobacterial pathogens or other unidentified environmental factors. In this context, it is noteworthy that the group-specific regression slopes between skin Gammaproteobacterial diversity and the multifunctional cytokine TGF-β were similar in all daycare groups and that the abundance of unidentified Faecalibacterium OTU 000008 in the gut was directly associated with plasma IL-17A in all daycare groups. *Faecalibacterium prausnitzii*, on the other hand, was associated with IL-17A in the nature-oriented group only; we recently showed that diverse vegetation, which is a proxy for diverse microbiota exposure, is associated with high *Faecalibacterium* abundance in the gut (*17*). The lack of *F. prausnitzii*–IL-17A association in standard daycare centers may result from low daily exposure to environmental biodiversity, while gut microflora in the intervention children might still be adapting to the new high-biodiversity living environment. To summarize, while associations between environmental factors and cytokines are complex, the current study highlights the profound effect of biodiversity intervention on commensal microbiota, which may explain partly divergent associations between plasma cytokines and microbiota in different daycare environments.

One of the major weaknesses of our study was the impossibility of controlling for the home environment. Families have different living environments, lifestyles, and children have varying numbers of siblings and pets. However, although families with a child in a nature-oriented daycare center may often be interested in various outdoor activities in their private life, this was not visible in the time spent outdoors or green areas. There is hardly any reason to assume an unknown bias between intervention and standard daycare centers in recruitment. Instead, we obviously cannot exclude the potential impact of a child's behavior outside daycare centers. These uncertainties highlight the problems inherent in all attempts to perform intervention trials in a normal living environment among families having young children, but they also underline the importance of a biodiverse daycare environment and the resulting strength of associations between skin and gut microbiota and the levels of immune markers, despite the multiple confounding factors in children's urban living environment.

In the intervention, we used slowly renewable natural forest floor, which is in limited supply. To cope with this issue, we recently proposed a wide-spectrum microbial inoculant from forest and agricultural materials that resembles microbiota in organic soils and hosts the wide spectrum of eukaryotic and prokaryotic microorganisms described above, including hundreds of inactive and slowly growing bacterial phylotypes (*19*, *20*). In a recent study (*36*), no facultative pathogens and less opportunistic pathogens were found on human skin after contact with playground sand enriched with the wide-spectrum microbial inoculant, compared to contact with standard playground sand or no contact at all. A two-week human exposure trial (*20*) with this wide-spectrum inoculant did not lead to any negative health outcomes for the study subjects. Providing that the preliminary results can be confirmed in subsequent intervention trials, the wide-spectrum PRR stimulation by biodiversity intervention may prove to be beneficial in modulating the immune system and microbial communities of urban dwellers (*36*).

Our trial has implications on the interpretation of the results from previous observational studies (*1*–*5*, *12*). The results of this study support the biodiversity hypothesis and the concept that low biodiversity in the modern living environment may lead to an uneducated immune system and consequently increase the prevalence of immune-mediated diseases (*4*, *5*). Similarly, while earlier studies have reported a decreased *Faecalibacterium* abundance in several immune disorders (*13*, *15*), we found that a high *F. prausnitzii* abundance is associated with decreased expression of proinflammatory cytokine IL-17A among healthy children. In conclusion, our study demonstrated that modifying the living environment of children with microbiologically diverse natural materials might provide a feasible approach for decreasing the risk of immune-mediated diseases in urban populations.

MATERIALS AND METHODS

Study group

The study was carried out in accordance with the recommendations of the Finnish Advisory Board on Research Integrity with approval from the ethics committee of the local hospital district (Pirkanmaa Hospital District, Finland). Written informed consent obtained from all guardians was in accordance with the Declaration of Helsinki.

Subjects attending daycare centers and living in an urban environment and meeting the inclusion criteria were eligible for participation in this study. Together, 75 children, aged between 3 and 5 years, participated in the study. Exclusion criteria of the study were the following: age below 3 or over 5 at the beginning of the study, native country other than Finland, immune deficiency (e.g., antibody deficiency and HIV infection), immunosuppressive medication (e.g., corticosteroids), a condition affecting immune response (e.g., rheumatoid arthritis, colitis ulcerosa, Crohn's disease, diabetes, and Down syndrome), or cancer diagnosis. The use of antibiotics, probiotics, medication, and other background information was recorded using standardized questionnaires.

Sample collection

To examine the effects of intervention on commensal microbiota and immune regulation, skin, stool, and blood samples were collected from the children before the yards were transformed and after the intervention period. Ground surface soil was collected before and after the intervention period from daycare yards located in Lahti. Before the intervention, samples were collected from sand boxes and playgrounds and, after the intervention, also next to swings and under the jungle gym.

A trained study nurse collected skin swab samples in daycare centers, and the children's parents collected stool samples at home. Skin swabs were taken from the back of the hand (5 cm–by–5 cm area),

10-s wiping with a saline buffer (0.1% Tween 20 in 0.15 M NaCl) wetted cotton wool stick. After sampling, the wool was cut to a sterile polyethene tube and frozen at −80°C until used for microbiome analyses. Stool samples were stored in home freezers (−18° to 20°C) until the researchers collected them and stored at −80°C.

A venous blood sample was taken from the arm vein into Vacutainer CPT Mononuclear Cell Preparation tubes with sodium citrate (BD Biosciences, NJ, USA) and centrifuged according to the manufacturer's instructions to separate the plasma and peripheral blood mononuclear cells (PBMCs). PBMCs were frozen in freezing medium consisting of 10% dimethyl sulfoxide (Merck KGaA, Darmstadt, Germany), 10% human AB serum (Sigma-Aldrich, MO, USA), penicillin (50 U/ml) and streptomycin (50 μg/ml; Sigma-Aldrich, MO, USA), and 10 mM L-glutamine (Life Technologies, CA, USA) in RPMI 1640 medium (Life Technologies, CA, USA) using freezing containers at −80°C (BioCision LLC, CA, USA). The PBMC samples were transferred into liquid nitrogen for long-term storage after 48 hours. The plasma samples were stored at −80°C.

Sample preparation for MiSeq sequencing and bioinformatics

Skin and stool samples for MiSeq sequencing were prepared as in the study of Roslund *et al.* (*11*). Soil, skin, and stool samples were sequenced using Illumina MiSeq 16*S* ribosomal RNA (rRNA) gene metabarcoding with read length 2 × 300 base pairs using a v3 reagent kit. Raw data were processed in Mothur (version 1.39.5) (*37*), as described by Roslund *et al.* (*10*).

Bacterial sequences were aligned against a SILVA reference (version 123) and classified using the Mothur version of Bayesian classifier with the RDP training set version 16 with 80% bootstrap threshold. Low-abundance OTUs (≤10) and OTUs detected in negative extraction and polymerase chain reaction (PCR) controls were removed from sequence data. There were 3 OTUs detected in skin, 0 OTUs in stool, and 21 OTUs (3 is the same that in skin) detected in soil DNA extraction or PCR control (Sterile water). Observed OTU richness and the Shannon diversity were calculated in Mothur. Soil and stool samples were subsampled to 3842 and skin samples to 329 sequence depth for bacterial community composition analyses. For skin samples, 13 of the 28-day samples were not collected or the number of sequences was too low, and thus, 29 children from intervention daycares, 19 from nature-oriented daycares, and 13 from standard daycares were included in skin sample analyses. Good's coverage index (average ± SD: soil, 0.96 ± 0.02; stool, 1.00 ± 0.00; skin, 0.96 ± 0.06) was used to determine OTU coverage adequacy for diversity and community composition analyses. Because statistical tests showed associations within the genus *Faecalibacterium*, OTUs of *Faecalibacterium* were further identified with microbe BLASTN (version 2.8.1+).

Cytokine and T_{reg} cell analyses

IL-17A and IL-10 concentrations were measured from plasma samples using a Milliplex MAP high-sensitivity T cell panel kit (Merck KGaA, Darmstadt, Germany) according to the manufacturer's instruction. Fluorescence was analyzed using a Bio-Plex 200 system (Bio-Rad Laboratories, Hercules, CA, USA), and data were collected using Bio-Plex Manager software (version 4.1, Bio-Rad Laboratories, Hercules, CA, USA). TGF-β1 concentration was analyzed using enzyme-linked immunosorbent assay (Bender MedSystems GmbH, Vienna, Austria).

Frozen PBMCs were thawed, and immunostaining to identify $CD3^+CD4^+CD25^+CD127^{low}FOXP3^+$ T_{reg} cells was performed as previously described (*38*). The frequency of T_{reg} cells was defined as a percentage of total $CD3^+CD4^+$ T cells.

Statistical analyses

All statistical tests were done in R version 3.4.2 (R Development Core Team, 2018) (*39*) with two-sided tests. Differences in community composition were analyzed with PERMANOVA (function adonis in vegan package) (*40*) with Bray-Curtis metric. PERMANOVA was analyzed with bacterial abundance and presence-absence datasets. PERMANOVA was done at OTU, genus, order, family, class, and phylum level and within some specific taxonomy if the relative abundance was more than 5% (skin and stool samples) and whenever there was a reason to assume biological relevance. In the data from stool samples, we analyzed differences in the compositional centroids of *Faecalibacterium* OTUs, as comparative studies between patients with immune system disorders and healthy individuals have reported decreased abundance of *Faecalibacterium* in the gut of the patients (*13*, *15*), and because the abundance of this clade in our data exceeded 5% data. NMDS was used with the Bray-Curtis metric to score the *Faecalibacterium* OTUs onto an ordination, and correlation with corresponding cytokine expression levels was assessed using the envit function in the vegan package in R. In skin samples, we analyzed Gammaproteobacterial communities because they have been connected to the living environment, expression of IL-10, and incidence of atopy (*4*). In stool and skin samples, we also analyzed taxa at the phylum, class, order, or family level if the abundance was more than 5%. As the abundance and diversity of bacteria in particularly organic soils is extremely high (*21*), for soil samples from the daycare yards, we analyzed taxa at the phylum, class, order, family, and genus levels with PERMANOVA if the abundance was more than 1%.

The Shannon diversity index was used to assess alpha diversity, and multivariate homogeneity of group dispersions (PERMDISP) was used to examine beta diversity. Differences in bacterial richness (Chao index, rarefied species, and observed OTU richness), alpha diversity, and relative bacterial abundances between daycare children were determined using ANCOVA or, in case of nonnormally distributed data, with the Kruskal-Wallis test. Gender was used as a covariate. Pairwise comparison was done with Tukey's honestly significant difference (HSD) test or with Dunn's test. The association between bacterial diversity and abundance changes, and cytokine expression levels and changes were evaluated using LMMs (function lmer in lme4 package). LMMs were constructed for bacterial taxonomy with observed changes, i.e., relative abundance, diversity, and richness changes during the intervention. In LMMs, cytokine expression or T_{reg} cell level change was used as a dependent variable, bacterial changes as explanatory variables, and daycare center as a random variable.

Differences between the time points were determined using the paired *t* test or, in case of nonnormally distributed data, with the Wilcoxon signed-rank test. To conceptualize the false discovery rate, all the statistical tests were carried out with Benjamini-Hochberg correction (referred to as P_{adj} in Results).

Primary population for the analysis was intention to treat (ITT). Per protocol (PP) (complete cases) population was used when changes between two time points (baseline and day 28) were analyzed. In addition, PP population for other analyses was used as a

sensitivity analysis to investigate whether conclusions are sensitive to assumptions regarding the pattern of missing data. These sensitivity analyses were done for significant results, i.e., skin and cytokine ANCOVA, and Ruminococcaceae and *Faecalibacterium* PERMANOVA.

The primary outcome measure for the power calculation is the difference between intervention and standard control daycare study subjects in the change of Gammaproteobacterial diversity on the skin between baseline and day 28. We used prior effect estimates from the previous study that estimate correlations between environmental biodiversity, human microbiota, and immune function (*4*).

SUPPLEMENTARY MATERIALS

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REFERENCES AND NOTES

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Review

What is the Healthy Gut Microbiota Composition? A Changing Ecosystem across Age, Environment, Diet, and Diseases

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Abstract: Each individual is provided with a unique gut microbiota profile that plays many specific functions in host nutrient metabolism, maintenance of structural integrity of the gut mucosal barrier, immunomodulation, and protection against pathogens. Gut microbiota are composed of different bacteria species taxonomically classified by genus, family, order, and phyla. Each human's gut microbiota are shaped in early life as their composition depends on infant transitions (birth gestational date, type of delivery, methods of milk feeding, weaning period) and external factors such as antibiotic use. These personal and healthy core native microbiota remain relatively stable in adulthood but differ between individuals due to enterotypes, body mass index (BMI) level, exercise frequency, lifestyle, and cultural and dietary habits. Accordingly, there is not a unique optimal gut microbiota composition since it is different for each individual. However, a healthy host–microorganism balance must be respected in order to optimally perform metabolic and immune functions and prevent disease development. This review will provide an overview of the studies that focus on gut microbiota balances in the same individual and between individuals and highlight the close mutualistic relationship between gut microbiota variations and diseases. Indeed, dysbiosis of gut microbiota is associated not only with intestinal disorders but also with numerous extra-intestinal diseases such as metabolic and neurological disorders. Understanding the cause or consequence of these gut microbiota balances in health and disease and how to maintain or restore a healthy gut microbiota composition should be useful in developing promising therapeutic interventions.

Keywords: gut microbiota; diversity; health; diet; nutrition; age; milk feeding; necrotizing enterocolitis; weaning; enterotypes; irritable bowel syndrome; inflammatory bowel disease; celiac disease; colorectal cancer; obesity; type 2 diabetes; Alzheimer's disease; Parkinson's disease; hepatic encephalopathy; autism spectrum disorders; personalized medicine

1. Introduction

The human gastrointestinal (GI) tract contains an abundant and diverse microbial community that gathers more than 100 trillion microorganisms [1]. The density of bacterial cells in the colon has been estimated at 10^{11} to 10^{12} per milliliter which makes the colon one of the most densely populated microbial habitats known on earth [2]. The gut microbiome encodes over 3 million genes producing thousands of metabolites, whereas the human genome consists of approximately 23,000 genes [3]. For years, scientists have been interested in gut microbiota, but one of the major difficulties in the relevant research has been the ability to culture these microorganisms [4]. During the last years, new technologies have allowed researchers to phylogenetically identify and/or quantify the components of the gut microbiota by analyzing nucleic acids (DNA and RNA) directly extracted from stools. The majority of these techniques are based on the extraction of DNA and the amplification of the 16S ribosomal RNA gene (rRNA) [5,6]. 16S rRNA sequencing has become the most useful technique to highlight diversity and abundance of the microbiome. The 16S rRNA gene sequences can be exploited with polymerase chain reaction (PCR) and metagenomics sequencing to characterize the microbial strains [7].

Considering the characteristics of gut microbiota such as the large diversity, the stability and resilience, and the symbiotic interaction with the host, we can define the host and the microorganisms inhabiting it as a "superorganism" [8,9] which performs immune and metabolic functions [1]. Gut bacteria are key regulators of digestion along the gastrointestinal tract; commensal bacteria play an important role in the extraction, synthesis, and absorption of many nutrients and metabolites, including bile acids, lipids, amino acids, vitamins, and short-chain fatty acids (SCFAs). Gut microbiota have a crucial immune function against pathogenic bacteria colonization inhibiting their growth, consuming available nutrients and/or producing bacteriocins. Gut microbiota also prevent bacteria invasion by maintaining the intestinal epithelium integrity [10]. Microorganisms prevent pathogenic colonization by many competition processes: nutrient metabolism, pH modification, antimicrobial peptide secretions, and effects on cell signaling pathways. Moreover, recent studies have identified a critical role for commensal bacteria and their products in regulating the development, homeostasis, and function of innate and adaptive immune cells [11]. It is paradoxical to note that the gut microbiota functions are highly preserved between individuals, whereas each individual's gut microbiota are characterized by a specific combination of bacterial species due to inter-individual and intra-individual variations throughout human life.

This review aims to define what would be the optimal gut microbiota composition in order to maintain these optimal microbiota immune and metabolic functions. After defining microbiota variations within and between individuals, we highlight the involvement of gut microbiota dysbiosis in various intestinal and extra-intestinal disorder development and we describe the strong relationship between gut microbiota diversity and health. We will see how these gut microbiota variations may have huge implications for intestinal and extra-intestinal disorders and, consequently, may influence health.

2. Gut Microbiota Variations

Gut microbiota are composed of several species of microorganisms, including bacteria, yeast, and viruses. Taxonomically, bacteria are classified according to phyla, classes, orders, families, genera, and species. Only a few phyla are represented, accounting for more than 160 species [12]. The dominant gut microbial phyla are Firmicutes, Bacteroidetes, Actinobacteria, Proteobacteria, Fusobacteria, and Verrucomicrobia, with the two phyla Firmicutes and Bacteroidetes [13] representing 90% of gut microbiota. The Firmicutes phylum is composed of more than 200 different genera such as *Lactobacillus*, *Bacillus*, *Clostridium*, *Enterococcus*, and *Ruminicoccus*. *Clostridium* genera represent 95% of the Firmicutes phyla. Bacteroidetes consists of predominant genera such as *Bacteroides* and *Prevotella*. The Actinobacteria phylum is proportionally less abundant and mainly represented by the *Bifidobacterium* genus [13]. Examples of taxonomic gut microbiota composition are illustrated in Figure 1.

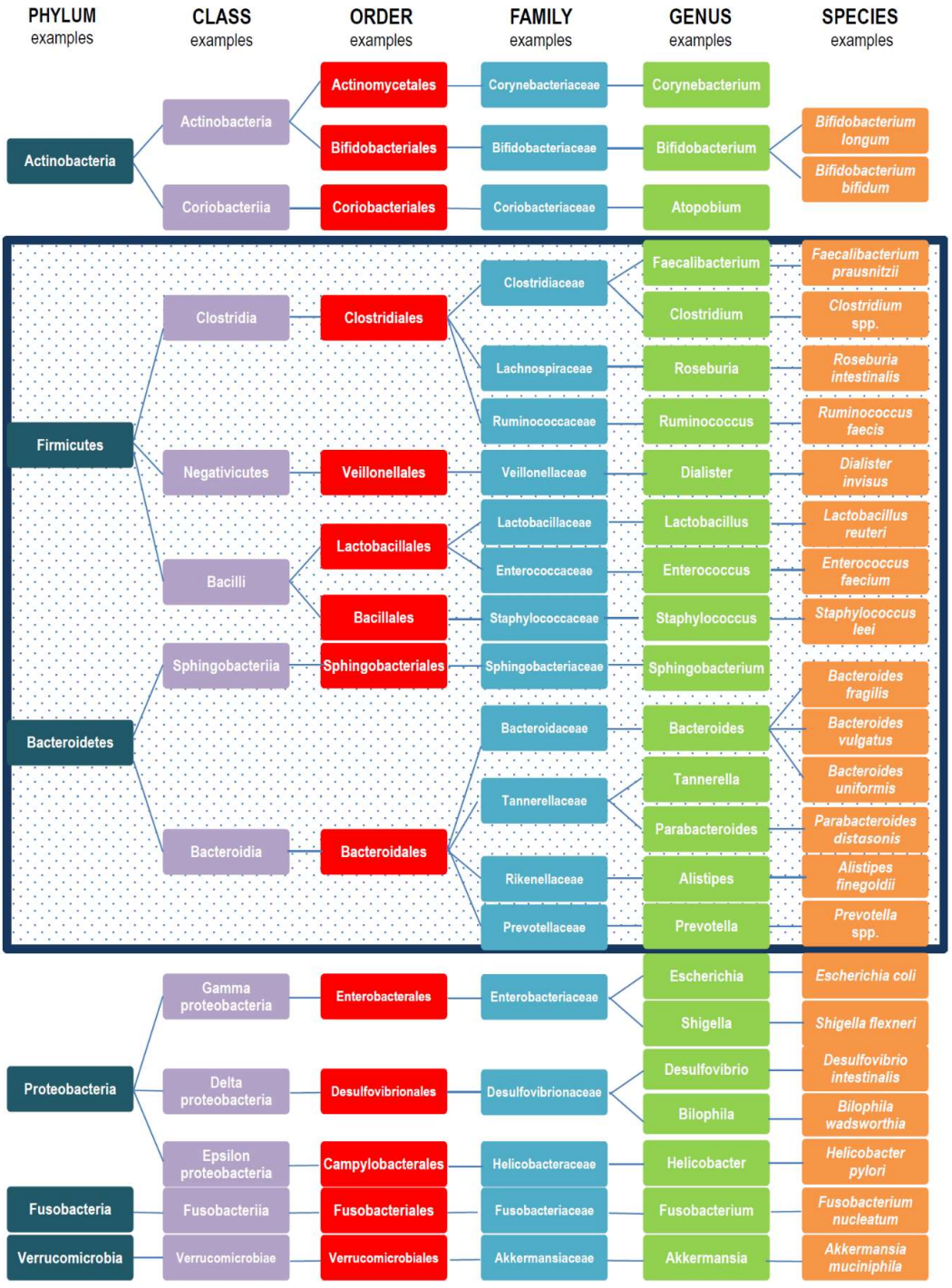


Figure 1. Examples of taxonomic gut microbiota composition. In the box are cited examples of bacteria belonging to Phyla Firmicutes and Bacteroidetes, representing 90% of gut microbiota.

2.1. Variations in the Same Individual

Human gut microbiota vary taxonomically and functionally in each part of the GI tract and undergo variations in the same individual due to infant transitions, age, and environmental factors such as antibiotic use. Microbiota variations within individuals are summarized in Table 1.

2.1.1. Intestine Anatomical Regions

Gut microbiota vary according to the intestine anatomical regions, which vary in terms of physiology, pH and O_2 tension, digesta flow rates (rapid in the mouth to the caecum, slower afterward), substrate availability, and host secretions [14]. The small intestine provides a more challenging environment for microbial colonizers given the fairly short transit times (3–5 h) and the high bile concentrations. The large intestine, which is characterized by slow flow rates and neutral to mildly acidic pH, harbors by far the largest microbial community (dominated by obligate anaerobic bacteria) [14]. We can observe a microbiota quantitative increasing gradient and a microbiota qualitative decreasing gradient with a progressive aerobic bacteria decrease for the benefit of strictly anaerobic bacteria (Table 1).

2.1.2. Infant Transitions

Birth Gestational Age

Birth gestational age is a major determinant of gut microbiota colonization. The microbiota composition of preterm infants (<37 weeks of gestation) is different from term counterparts (Table 1). In preterm infants, after birth, the microbiota colonization is challenged by organ immaturity and environmental factors such as antibiotic use, hospital stay [15], and enteral feeding [16]. For these reasons, the postnatal maturation of gut and systemic immunity may be highly affected by preterm birth [16].

In a new-born pig model, an analysis of the gut microbiota composition of preterm and term pigs showed that *Ruminococcus* spp., some *Enterobacterium* spp., *Lachnospiraceae*, *Peptostreptococcaceae*, and *Clostridiaceae* were dominant genera in both preterm and term pigs. However, a higher *Enterococcus* spp. abundance in preterm than term pigs was found [16].

Preterm infants show low diversity with an increased colonization of potentially pathogenic bacteria from the *Enterobacteriaceae* family of the Proteobacteria phylum [15] and reduced levels of strict anaerobes such as *Bifidobacterium* [17], *Bacteroides*, and *Atopobium* [15].

Human milk composition depends on genetic factors and the mother's secretor and Lewis blood groups defining four phenotypes characterized by different levels of oligosaccharide amounts [18]. Higher levels of Proteobacteria and lower levels of Firmicutes are noted in premature infants of non-secretor mothers [19]. A recent study by Praticò et al. [20] characterizing human breast milk composition demonstrated that human milk oligosaccharides (HMOs) related to different mother phenotypes modulate gut microbiota composition in infants. Specifically, HMOs associated with secretor mothers may have a protective prebiotic effect by decreasing pathogens associated with sepsis and necrotizing enterocolitis (NEC) [19]. This indicates that HMOs may influence the intestinal microbiota and prevent gut dysfunction and NEC in preterm infants [21].

Lactoferrin (LF) is another well-known component of human milk favoring gut infant colonization with beneficial bacteria and consequently representing a crucial role played in preterm infants' microbiota [22]. Indeed, correlations between LF and beneficial microbiota in breast milk and infant's feces have been demonstrated [22]. High levels of fecal LF, particularly in preterm infants, may represent an important factor in the initiation, development, and/or composition of the neonatal gut microbiota contributing to the immunologic maturation and well-being of the newborn, especially in preterm infants [22].

Therefore, a mother's own milk helps to shape developing core gut microbiota that can improve growth and neurodevelopment and decrease the risk of NEC and late-onset sepsis [19,21]. It is for all these reasons that human milk should be the primary enteral diet of premature infants.

Type of Delivery

At birth, the intestine is sterile and devoid of bacteria. After birth, a rich and dynamic ecosystem develops from mother's skin, vaginal and fecal microbiota, and environment microbiota contacts. Microbiota colonization varies according to the type of delivery [23–25] (Table 1).

With regard to vaginal delivery, newborns acquire a microbiota composition resembling their mother's vaginal microbiota. Indeed, an analysis of the meconium of newborn infants [24] revealed a strong correlation between the microbiota of the newborn digestive tract and the microbial communities of the mother's vagina: *Lactobacillus*, *Prevotella*, and *Sneathia*. Biasucci et al. [25] showed that the microbiota of vaginally delivered infants are also characterized by predominant groups such as *Bifidobacterium longum* and *Bifidobacterium catenulatum*. Other facultative anaerobic species such as *Escherichia coli*, *Staphylococcus*, *Bacteroides fragilis*, and *Streptococcus* colonize the infant gut [26–28].

On the contrary, infants born by cesarean section (C-section) acquire bacteria derived from hospital environment and mother's skin: *Staphylococcus*, *Corynebacterium*, *Propionibacterium* spp. [24, 29]. *Escherichia*, *Shigella*, and *Bacteroides* species are underrepresented in infants born by cesarean delivery [29]. The intestinal microbiota of neonates delivered by cesarean delivery are less diverse in terms of bacteria species than the microbiota of vaginally delivered infants [25].

Differences between the microbiota of C-section and vaginally born infants have been also detected in analyses performed at 7 years of age [23]. Cesarean birth has been associated with an increased risk of chronic immune disorders such as asthma, systemic connective tissue disorders, juvenile arthritis, inflammatory bowel disease [30], and obesity [31].

Methods of Milk Feeding

Studies have demonstrated that formula-fed infants are more often colonized with *Escherichia coli*, *Bacteroides*, and *Clostridium difficile* compared with breastfed infants [29,32]. Regarding Actinobacteria abundance, *Bifidobacterium* spp. have been associated with breastfeeding and formula milk [33,34]. However, breastfed infants generally harbor a more complex and diverse *Bifidobacterium* microbiota than formula-fed infants [34]. Breastfed infants are provided with microbiota having more than a two-fold increase in the number of *Bifidobacterium* cells compared to formula-fed infants [33]. Breastfed infants have more beneficial gut microbiota, with a higher richness and diversity of *Bifidobacterium* spp. and a lower number of *Clostridium difficile* and *Escherichia coli* than formula-fed infants [32] (Table 1).

Bifidobacterium spp. are responsible for the fermentation of galactooligosaccharide (GOS), one of the main components of breast milk, to produce SCFAs [35]. Indeed, *Bifidobacterium* spp. have an enzyme named lacto-N-biosidase, which facilitates the assimilation of GOS [36]. If *Bifidobacterium* quantity increases, the quantity of HMOs in feces decreases causing elevated acetate and lactate concentrations and decreasing pH [37]; an HMO consumption by Bifidobacteria in the infant's gut may suggest a prebiotic effect of HMOs on gut infant microbiota by selectively stimulating *Bifidobacterium* spp. [37]. Another prebiotic effect of β-palmitate, a natural human milk fatty acid and a component of some infant formulas, on gut infant microbiota was demonstrated by positively influencing *Bifidobacterium* spp. (and *Lactobacillus* spp.) abundance [38].

Furthermore, the maintenance of a healthy and balanced mother's gut microbiota during pregnancy is also considered as an important factor in positively influencing the milk microbiota composition [39]. Additionally, oral probiotic supplementation in mothers with vaginal delivery may increase breast milk *Bifidobacterium* spp. and *Lactobacilli* spp. abundance [39].

These studies have shown that native core microbiota are shaped during early life: the profile of intestinal microbiota in the full-term, vaginally delivered, and breastfed infant with healthy and balanced mother's milk microbiota is considered healthy. Researches should seek to demonstrate the role of this native core microbiota composition on gut health and subsequent diseases.

Weaning Period

The introduction of solid foods and the termination of milk-feeding/weaning coincide with major gut microbiota changes. The abundance of genera *Bifidobacterium*, *Clostridium coccoides*, and *Bacteroides* are predominant after weaning [40]. The microbiota of breastfed children and the microbiota of children previously fed with formula milk become closer to each other (Table 1).

Dietary habits, infant weaning, and feeding practices become determinants and play a crucial role in gut microbiota variations. The introduction of high-fiber and carbohydrate foods (traditional foods) causes an increase in Firmicutes and *Prevotella*, whereas the introduction of high-fiber and animal protein foods causes an increase in Bacteroidetes [41]. Furthermore, Fallani et al. [40] demonstrated that northern European countries are associated with a higher proportion of Bifidobacteria in the infant gut microbiota, whereas higher levels of *Bacteroides* and *Lactobacilli* characterize southern European countries.

2.1.3. Age

At one year old, a child's microbiota composition has a characteristic abundance of *Akkermansia muciniphila*, Bacteroides, *Veillonella*, *Clostridium coccoides* spp., and *Clostridium botulinum* spp. [42].

Microbiota diversity increases with age until it becomes a stable adult microbiota composition dominated by three bacterial phyla (Table 1): Firmicutes (*Lachnospiraceae* and *Ruminococcaceae*), Bacteroidetes (*Bacteroidaceae*, *Prevotellaceae*, and *Rikenellaceae*), and Actinobacteria (*Bifidobacteriaceae* and *Coriobacteriaceae*) that are the result of maturation due to the influence of genetics, environment, diet, lifestyle, and gut physiology [42]. At approximately three years of age, a child's gut microbiota composition and diversity are most like those of adults [43].

With regard to older people over the age of 70, gut microbiota composition can be affected by digestion and nutrient absorption changes and immune activity weakness. Dietary habit changes (more monotonous) may also weaken gut microbiota diversity. A decrease in anaerobic bacteria such as *Bifidobacterium* spp. and an increase in *Clostridium* and Proteobacteria have been observed [44]. Given the role of *Bifidobacterium* spp. in the stimulation of the immune system and metabolic processes, a Bifidobacteria decrease may partially explain low systemic inflammatory status and malnutrition in older adults [45].

2.1.4. Antibiotics

Gut microbiota composition can be more or less affected by antibiotic use. A follow-up study explored the effect of antibiotics with different modes of action on human gut microbiota composition [46] and demonstrated that antibiotic treatments modify the gut microbiota composition with an abundance/appearance of certain species and a decrease/disappearance of other species (Table 1). Broad-spectrum antibiotics lead to an imbalance between Firmicutes and Bacteroidetes. The bacterial diversity decreases and so does the abundance of these bacteria during the treatments. The alteration of microbiome composition depends on the antibiotic class, dose, period of exposure, pharmacological action, and target bacteria [47] (Table 1). Specific properties of antibiotics such as antimicrobial effects or mode of action are powerful forces for the selection of intestinal microbiota and are partially responsible for the shifts in bacterial composition during antibiotic therapy [46].

Each class of antibiotics has different properties and excretion systems, resulting in different patterns of alteration in the microbiome composition [47].

A cultivation-independent survey of gut microbiota composition of three persons before, during, and after two exposures to the same antibiotic (ciprofloxacin) [48] has been conducted. This study revealed a considerable resilience to antibiotic administration but also suggested that, in some cases, the system retains a memory of past disturbance and that, in all cases, repeated disturbance leads to a persistent regime shift [48]. The impact of antibiotic disturbance on the resilience of microbiota during future antibiotic treatments can thus also vary considerably across individuals [49].

Table 1. Microbiota variations within individuals.

		Gut Microbiota Abundance							Bacteria Diversity	Ref.
		Actinobacteria	**Bacteroidetes**	**Firmicutes**	**Proteobacteria**	**Fusobacteria**	**Verrucomicrobia**	**Euryarchaeota**		
Anatomical part of gut tract	**Small intestine**			*Lactobacillus*	*Enterobacteriaceae* *					[14]
	Colon		*Bacteroidaceae* * *Prevotellaceae* * *Rikenellaceae* *	*Lachnospiraceae* * *Ruminococcaceae* *						
Gestational age	**Preterm birth (<37 weeks of gestation)**	*Bifidobacterium* spp.↓ *Atopobium* spp.↓	Bacteroides *↓ (non-secretor mothers)	Firmicutes *↓ (non-secretor mothers) *Lactobacillus*↑ *Ruminococcus* spp. *Lachnospiraceae* * *Peptostreptococcaceae* * *Clostridiaceae* *	*Enterobacteriaceae* *↑ *Enterococcus* spp.↑				↓	[15,16,19]
	Full-term birth	*Bifidobacterium* spp.↑	Bacteroidetes *↑	*Ruminococcus* spp. *Lachnospiraceae* * *Peptostreptococcaceae* * *Clostridiaceae* *	*Enterobacteriaceae* *				↑	[16,20]
Type of delivery	**Vaginal delivery**	*Bifidobacterium* spp.↑ *Bifidobacterium longum*↑ *Bifidobacterium catenulatum*↑	*Prevotella*↑ *Bacteroides fragilis*↑	*Lactobacillus*↑ *Staphylococcus*↑ *Streptococcus* ↑	*Escherichia*↑	*Sneathia*↑			↑	[22–26]
	C-section	*Corynebacterium*↑ *Propionibacterium*↑	*Bacteroides* *↓	*Staphylococcus*↑	*Escherichia*↓ *Shigella*↓				↓	[21–23,27]
Methods of (milk) feedings	**Breast milk**	*Bifidobacterium*↑↑		*Lactobacillus*↑ *Staphylococcus* ↑	*Enterococcus*↑				↑	[27,30–32,38]
	Artificial milk	*Bifidobacterium*↑	*Bacteroides*↑	*Clostridium*↑ *Clostridium difficile*↑ *Lactobacillus*↑	*Escherichia*↑				↓	[27,30–32]
	Introduction of solid food	*Bifidobacterium*↑	Bacteroidetes *↑ *Bacteroides*↑	Firmicutes *↑ Lactobacilli↑ *Clostridium coccoides*↑					↑	[36,37]

Table 1. *Cont.*

		Gut Microbiota Abundance							Bacteria Diversity	Ref.
		Actinobacteria	**Bacteroidetes**	**Firmicutes**	**Proteobacteria**	**Fusobacteria**	**Verrucomicrobia**	**Euryarchaeota**		
Human age	**Childhood (first year of life)**	*Bifidobacterium*	*Bacteroides*	*Veillonella* *C. coccoides* *C. botulinum*			*Akkermansia muciniphila*		↑	[38,39]
	2–3 years old to adult	*Bifidobacteriaceae* * *Coriobacteriaceae* *	*Bacteroidaceae* * *Prevotellaceae* * *Rikenellaceae* *	*Lachnospiraceae* *Ruminococcaceae*	Proteobacteria *	*Fusobacteria* *	*Akkermansia muciniphila*	*Methanobrevibacter smithii*	↑	[38]
	Over 70	*Bifidobacteriaceae*↓		*Clostridium* *↓	Proteobacteria *↑				↓	[40]
Antibiotic treatments	**Macrolide**	Actinobacteria *↓	*Bacteroides*↑	Firmicutes *↓	Proteobacteria *↑				↓	[43]
	Clarithromycin	Actinobacteria *↓	*Bacteroides*↑	Firmicutes *↓	Proteobacteria *↑				↓	
	Vancomycin			*Lactobacillus*↓ *Clostridium*↓					↓	
	Ciprofloxacin	*Bifidobacterium*↓	*Alistipes*↓ Bacteroides↑	*Faecalibacterium*↓ *Oscillospira*↓ *Ruminococcus*↓ *Dialister*↓					↓	
	Clindamycin	*Bifidobacteriaceae*↓ *Lactobacillus*↓							↓	

* Unknown genera.

2.2. Gut Microbiota Variations between Individuals

We highlighted that the gut microbiota composition varies in the same individual and we will see that it also changes between individuals. These inter-individual variations are principally due to enterotypes, body mass index (BMI) level, and external factors such as lifestyle, exercise frequency, ethnicity, and dietary and cultural habits. The microbiota abundance variations between individuals are illustrated in Table 2.

2.2.1. Enterotypes

Gut microbiota of each individual are specifically characterized by clusters of bacteria named enterotypes [13]. Three enterotypes are characterized by three dominant bacteria clusters (Table 2): *Bacteroides* (enterotype I), *Prevotella* (enterotype II), or *Ruminococcus* (enterotype III). Each enterotype harbors different bacteria genera (Table 1). These three enterotypes are not only enumerations of bacteria; they are also specifically regrouped by functions. Indeed, an enterotype is a functional harmonious association of several bacteria species rather than a systematic addition of bacteria species. Every enterotype is not a clear-cut identity such as blood groups; however, enterotypes characterize individuals, remain stable from adulthood, and can be restored if they are modified. Each enterotype with its distinctive clusters of bacteria and respective functional characteristics defines a distinctive way of generating energy from fermentable substrates available in the colon. Indeed, bacteria clusters of enterotype I derive energy primarily from carbohydrates using principally glycolysis and pentose phosphate pathways, whereas bacteria clusters of enterotypes II and III are able to degrade mucin glycoproteins of the gut mucosal layer. Enterotypes seem to be principally defined according to dietary habits. Understanding the origins and functions of enterotypes may improve the knowledge of the relationships between gut microbiota and human health.

2.2.2. Body Mass Index (BMI) Classes

Several studies [50,51] have examined the impact of childhood BMI on gut microbiota composition and demonstrated that children with overweight or normal BMI are provided with a higher microbial diversity than underweight children. Gut microbiota diversity descends stepwise based on BMI class [50,52].

Bervoets et al. [53] demonstrated that the microbiota of obese children are provided with an elevated Firmicutes-to-Bacteroidetes ratio compared to the microbiota of lean children [53]. Furthermore, low relative proportions of *Bifidobacterium vulgatus* and high concentrations of *Lactobacillus* spp. are observed in the obese microbiota [53]. Riva et al. [54] confirmed that obesity is associated with elevated levels of Firmicutes such as *Ruminococcaceae* and depleted levels of Bacteroidetes such as *Bacteroidaceae* and *Bacteroides*. SCFAs are higher in obese children suggesting elevated substrate utilization. These findings suggest that the dysbiosis of gut microbiota may contribute to the pathophysiology of obesity and the increased ratio of Firmicutes to Bacteroidetes is associated with the increased production of SCFAs and energy harvest from colonic fermentation [54].

The underweight BMI level also revealed profound gut microbiota variations. Borgo et al. [55] performed a comprehensive data analysis comparing gut microbiota and anthropometric traits of 15 anorexia nervosa (AN) women and healthy controls. Results showed that AN intestinal microbiota showed a significant increase in *Enterobacteriaceae* and *Methanobrevibacter smithii* compared with healthy controls [55]. On the contrary, the genera *Roseburia*, *Ruminococcus*, and *Clostridium* were depleted in line with the observed reduction in AN of the total SCFAs [55].

BMI levels represent a valid predictive value for gut microbiota dysbiosis. Studies have demonstrated that gut microbiota variations are correlated with increased or depleted production of SCFAs that may respectively contribute to the pathophysiology of obesity or AN. Interventions such as prebiotics and probiotics may be possible solutions to manage both pediatric obesity [50] and AN patients.

2.2.3. Ethnicity, Dietary Habits, and Cultural Habits

While the microbiome of a healthy individual is relatively stable, gut microbial dynamics can certainly be influenced by lifestyle and dietary cultural choices [56]. A study of European children (fed with the Western diet) and Burkina Faso children (assuming a diet rich in millet/sorghum + local vegetables containing very few lipids and animal proteins) [57] revealed that African children's microbiota have a remarkable abundance of *Prevotella* and *Xylanibacter*. Furthermore, *Shigella* and *Escherichia* are widely under-represented. Another study [58] compared Hadza hunter-gatherers and Italian gut microbiota. At the phylum level, Hadza gut microbiota are largely enriched in Proteobacteria and Spirochaetes, which are extremely rare in the Italian gut microbiota, whereas Actinobacteria, an important subdominant component of the Italian gut microbiota, are almost absent. At the genus level, Hadza gut microbiota are comparatively enriched in *Prevotella*, *Eubacterium*, *Oscillibacter*, *Butyricicoccus*, *Sporobacter*, *Succinivibrio*, and *Treponema* and correspondingly depleted in *Bifidobacterium*, *Bacteroides*, *Blautia*, *Dorea*, unclassified *Lachnospiraceae*, *Roseburia*, *Faecalibacterium*, *Ruminococcus,* and unclassified *Erysipelotrichaceae*. These two studies showed that African gut microbiota have clearly an enterotype *Prevotella* (enterotype II); the African diet rich in millet/sorghum + local vegetables containing very few lipids and animal proteins allows a mucine degradation in synergy with *Desulfovibrionaceae*. European gut microbiota (Western diet) have principally an enterotype *Bacteroides* (enterotype I): the European diet rich in lipids and animal proteins allows energy production from carbohydrates and proteins through fermentation [13]. David et al. [59] compared plant-based diet microbiome (high fibers and low fats and proteins) with animal-based diet microbiome (low fibers and high fats and proteins) and respective changes in microbiome on either diet and demonstrated that a shift toward an animal-based diet increases the abundance of bile-tolerant microorganisms (*Alistipes*, *Bilophila*, and *Bacteroides*) and decreases the levels of Firmicutes that metabolize dietary plant polysaccharides (*Roseburia*, *Eubacterium rectale*, and *Ruminococcus bromii*). Moreover, microbial activity trades off between carbohydrate and protein fermentation when the type of diet respectively changes. This change occurred only one day after the diet reached the distal gut microbiota. David et al. [59] showed that diet alters human microbiota rapidly and reproducibly.

2.2.4. Exercise Frequency

Bai et al. [50] suggested associations of exercise frequency with gut microbiota composition of young children and adolescents. Daily exercise increases gut microbial diversity (Table 2) with a Firmicutes enrichment microbiota: *Clostridiales, Roseburia, Lachnospiraceae*, and *Erysipelotrichaceae* by producing more SCFAs which may increase the expression of tight junction proteins in colon epithelia to heighten the resistance of the intestinal barrier, reduce mucosal permeability, and inhibit inflammatory cytokines [50,60].

Clarke et al. [61] explored exercise and protein consumption for their impact on the gut microbiota of professional athletes from an international rugby union squad. A higher alpha diversity of gut microorganisms representing more than 20 distinct phyla has been demonstrated in athletes compared with high and low BMI controls [61]. Indeed, this study showed that exercise increases gut microbial diversity (Table 2) and protein consumption positively correlates with microbial diversity. These results provide evidence for a beneficial impact of exercise on gut microbiota diversity, but also indicate that the relationship exercise–microbiota diversity is probably related to accompanying dietary extremes [61].

Table 2. Microbiota variations between individuals.

		Gut Microbiota Abundance							Bacteria Diversity	Ref.
		Actinobacteria	**Bacteroidetes**	**Firmicutes**	**Proteobacteria**	**Verrucomicrobia**	**Euryarchaeota**	**Spirochaetes**		
Enterotype	**I**	*Slackia*	*Bacteroides* [(1)] *Parabacteroides*	*Clostridiales* * *Alkaliphilus* *Lactobacillus* *Catenibacterium*	*Geobacter*		*Methanobrevibacter smithii*			[13]
	II	*Eggerthella*	*Prevotella* [(1)]	*Veillonella* *Ruminococcaceae* * *Holdemania* *Peptostreptococcaceae* * *Staphylococcus* *Leuconostoc*	*Desulfovibrionaceae* * *Rhodospirillum* *Helicobacter* *Escherichia* *Shigella*	*Akkermansia muciniphila*				
	III	*Gordonibacter*	*Sphingobacterium*	*Ruminococcus* [(1)] *Staphylococcus* *Marvinbryantia* *Symbiobacterium* *Ruminococcaceae* * *Dialister*		*Akkermansia muciniphila*				
BMI level (among children and adolescents)	**Overweight to obese level**	*Bifidobacterium*↑ *B. vulgatus*↓	Bacteroidetes *↓	*Lactobacillus*↑ Firmicutes *↑	Proteobacteria *↑				↓	[46,47,49,50]
	Underweight level			*Roseburia* spp.↓ Ruminococcus↓ Clostridium spp.↓	*Enterobacteriaceae* *↑		*Methanobrevibacter smithii*↑		↓	[46,51]
Exercise frequency	**High performance sport**		*Bacteroides*↓	*Ruminococcaceae* *↑ *Lactobacillus*↓ *Lactobacillaceae* *↓	*Succinivibrionaceae* *↑	*Akkermansiaceae*↓			↑	[57]
	Children and adolescents daily exercise			*Clostridiales*↑ *Roseburia*↑ *Lachnospiraceae*↑ *Erysipelotrichaceae*↑					↑	[46]
Type of diet, communities, climate, and geographical sites	**High-fiber diet (African diet)**	*Bifidobacterium*↓	*Prevotella*↑ *Bacteroides*↓	*Eubacterium*↑ *Oscillibacter*↑ *Butyricicoccus*↑ *Sporobacter*↑ *Blautia*↓ *Dorea*↓ *Lachnospiraceae* *↓ *Roseburia*↓ *Faecalibacterium*↓ *Ruminococcus*↓ *Erysipelotrichaceae* *↓	*Succinivibrio*↑			*Treponema*↑	↑	[53,55]
	High-fat and animal protein diet (Western diet)	Actinobacteria *↑	*Bacteroides*↑ *Alistipes*↑ *Barnesiella*↑	*Roseburia*↓ *Eubacterium rectale*↓ *Ruminococcus bromii*↓	*Bilophila*↑				↓	

* Unknown genera. [(1)] Main genera.

3. Gut Microbiota Variations in Health and Disease

Gut microbiota composition is highly variable. The variation itself is considered as physiological in the context of healthy gut microbiota, according to age, ethnicity, lifestyle, and dietary habits. However, these physiological gut microbiota variations have huge implications in intestinal and extra-intestinal disorders. Indeed, dysbiosis is often defined as an alteration of gut microbiota composition and a cause or a consequence of disorders. It is often difficult to ascertain whether the change is beneficial or detrimental. As for the human conditions, changes represent a challenge for a better adaptation in a new context and may potentiate resilience. However, a chronic external stimulation may be stressful and disruptive for an unstructured ecosystem. We will discuss the correlations between several diseases and alterations of gut microbiota composition.

3.1. Intestinal Disorders

3.1.1. Irritable Bowel Syndrome

Irritable bowel syndrome (IBS) is one of the most common gastrointestinal (GI) disorders and the bacterial role has been largely investigated [62].

The study [63] of fecal and colonic mucosal biopsy samples from IBS patients and healthy controls demonstrated a significant reduction in the concentration of aerobic bacteria such as the *Lactobacillus* species in fecal samples from IBS patients compared to healthy controls. Another study [64] demonstrated that the microbial communities of IBS patients are enriched in Proteobacteria and Firmicutes but reduced in Actinobacteria and Bacteroidetes compared to controls. In particular, 16S rDNA sequences belonging to the family *Lachnospiraceae* within the phylum Firmicutes are in greater abundance in the IBS clone library [64].

Other studies [62,65] confirmed and revealed some phyla and genera variations in IBS patients compared to healthy controls: an increase in the Firmicutes-to Bacteroidetes-ratio, a decrease in some Firmicutes families (*Lactobacilli*, *Faecalibacterium*) and the Actinobacteria population (Bifidobacteria, *Collinsella*), and an increase in some Firmicutes families (*Veillonella, Streptococci*, *and Ruminococcus* spp.) and in Proteobacteria (*Enterobacteriaceae* spp.). Therefore, these findings demonstrated a loss of microbial richness that may be involved in amino acid synthesis, in the integrity of cellular junctions, and in inflammatory response, suggesting a weakness of the epithelial barrier functions partially explaining IBS symptoms.

3.1.2. Inflammatory Bowel Disease (IBD)

Inflammatory bowel diseases (IBD) gather idiopathic, chronic, and relapsing inflammatory conditions of the gastrointestinal tract including ulcerative colitis (UC) and Crohn's disease (CRD).

The findings of Frank et al. [66] indicated a diminution of *Lachnospiraceae* and Bacteroidetes microbial populations and an increase in Proteobacteria families in IBD patients compared to control gut microbiota.

Gut microbiota variations appear to be different between UC and CRD. Indeed, a decreased abundance of the butyrate-producing bacteria *Roseburia hominis* and *Faecalibacterium prausnitzii* has been observed in UC patients relative to controls [67], whereas the opposite has been observed in CRD patients, who are provided with increased *Faecalibacterium prausnitzii* levels in addition to a reduced overall diversity [68].

In the case of CRD patients, another study [69] demonstrated a decrease in *Dialister invisus*, an uncharacterized species of *Clostridium* spp., in *Faecalibacterium prausnitzii*, and in *Bifidobacterium adolescentis* and an increase in *Ruminococcus gnavus*.

Sokol et al. [70] confirmed the reduction of *F. prausnitzii* in CRD patients and also demonstrated that an oral administration of live *Faecalibacterium prausnitzii* reduced the severity of colitis and tended to correct the dysbiosis. These results suggest that counterbalancing dysbiosis using *Faecalibacterium prausnitzii* as a probiotic is a promising strategy in CRD treatment [70].

These results do not demonstrate a causal relationship between microbial dysbiosis and IBD pathophysiology, but they rather suggest that gut microbial unbalances are likely to contribute to disease severity.

3.1.3. Celiac Disease

Celiac disease (CD) is a chronic intestinal inflammatory disorder due to an aberrant immune response to dietary gluten proteins in genetically predisposed individuals.

Gut microbiota variations may play a significant role in the pathogenesis of CD; indeed, dysbiosis is linked with an inflammatory milieu in celiac patients [71]. Celiac disease is caused by the interplay between gluten, genetic factors, and environmental factors such as gut microbiota [72].

Studies [73–76] have demonstrated that *Bifidobacterium* spp., *Bifidobacterium longum*, *Clostridium histolyticum*, *C. lituseburense,* and *Faecalibacterium prausnitzii* group proportions are less abundant in untreated CD patients than in healthy controls. Indeed, patients with CD show a reduction in beneficial species (*Lactobacillus* and *Bifidobacterium*) and an increase in those potentially pathogenic (*Bacteroides* and *E. coli*) as compared to healthy subjects [74]. The mucosal layer of CD patients fails to stabilize the gut microbiota and fails to prevent the host from the invasion of harmful antigens and pathogens [71]. This dysbiosis is reduced, but may still remain, after a gluten-free diet [71,73].

3.1.4. Colorectal Cancer (CRC)

Colorectal cancer is the third most common cause of cancer mortality in the world [77]. Structural fecal bacterial segregations between CRC patients and healthy volunteers have been demonstrated [78]. The gut microbiota of the CRC patients were enriched in *Bacteroides fragilis*, *Enterococcus*, *Escherichia/Shigella*, *Klebsiella*, *Streptococcus*, and *Peptostreptococcus* and were impoverished in *Roseburia* and other butyrate-producing bacteria of the family *Lachnospiraceae* [78]. The gut microbiota of the healthy volunteers were enriched in *Bacteroides vulgatus* and *Bacteroides uniformis*. Therefore, gut microbiota variations, such as a reduction of butyrate producers and an increase in opportunistic pathogens, constitute a major structural imbalance of gut microbiota in CRC patients.

Shen et al. [79] demonstrated a higher abundance of Proteobacteria and a lower abundance of Bacteroidetes in CRC cases compared to controls. At the genus level, CRC cases showed an increased abundance of *Dorea* spp. and *Faecalibacterium* spp. and lower proportions of *Bacteroides* spp. and *Coprococcus* spp. than controls.

Genomic analysis identified an association of *Fusobacterium* spp. with colorectal cancer [80]; the microbiota of CRC patients were enriched in *Fusobacterium* spp., whereas the Bacteroidetes and Firmicutes phyla were depleted. Furthermore, *Fusobacterium* spp. may contribute to tumorigenesis by an inflammatory-mediated mechanism [80], but the precise role of Fusobacteria in colorectal carcinoma pathogenesis requires further investigation.

All these findings reveal alterations in CRC microbiota that may contribute to the etiology of colorectal cancer. The extension of these findings may lead to strategies able to manipulate microbiota to prevent colorectal cancer as well as to identify individuals at high risk [79].

3.2. Extra-Intestinal Disorders

We highlighted that the pivotal relationship between gut microbiota and the host is involved in many intestinal disorders. Recent advances in research have demonstrated that this mutualistic gut microbiota–host relationship appears to play a critical role for many extra-intestinal diseases such as metabolic diseases and neurological disorders with “gut–brain axis” interactions [81], but also for complex multifactorial diseases such as age-related macular degeneration with “gut–retina axis” interactions [82].

3.2.1. Metabolic Disorders

Obesity

Animal studies constitute the majority of causative evidence linking changes in microbial composition to obesity while, in humans, data are more variable. In addition, although the majority of mouse gut species are unique, the mouse and human microbiota are similar at the division level, with Firmicutes and Bacteroidetes dominating [83].

The analysis [83] of gut microbiota of genetically obese ob/ob mice and lean mice all fed the same polysaccharide-rich diet revealed a lower relative abundance (50%) of Bacteroidetes in obese ob/ob mice, whereas the Firmicutes are correspondingly higher. Indeed, higher numbers of *Ruminococcaceae* and *Rikenellaceae* have been observed in leptin-resistant obese (leptin-promoting satiety) and diabetic mice (db/db) compared with their lean littermates [84]. In addition, the higher abundance of *Ruminococcaceae* and *Rikenellaceae* in mice fed a high-fat diet is not only dependent on the ingested diet but is also closely linked with obesity and type 2 diabetes [85]. Furthermore, the association between *Desulfovibrionaceae* abundance and obesity and type 2 diabetes has been demonstrated [86,87]. Other studies [50,88] confirmed the role of Proteobacteria in obesity by producing pro-inflammatory molecules such as lipopolysaccharides and helping to harvest energy and increase host fat storage [88].

On the contrary, researchers [86,89] have recently demonstrated that *Akkermansia muciniphila*, a mucin-degrading bacteria living in the mucus layer [90], decreases in both genetically and diet-induced obese mice.

All these studies highlight the finding that obesity is associated with changes in the composition of gut microbiota including lower species diversity and shifts in the abundance of genes involved in metabolism. These gut microbiota variations affect the microbiome which has an increased capacity to harvest energy from the diet and these changes are transmissible [91]. Gut microbiota can be considered as a contributing factor to the pathophysiology of obesity and may have potential therapeutic implications.

Type 2 Diabetes (T2D)

Several studies [92,93] demonstrated that gut microbiota composition is altered in patients suffering from T2D, but it is not clear whether these changes are a cause or simply a consequence of the disorder.

Larsen et al. [92] showed that the proportions of phyla Firmicutes and *Clostridia* are significantly reduced in the T2D sufferers compared to the healthy group. Furthermore, the ratios of Bacteroidetes to Firmicutes, the ratios of *Bacteroides-Prevotella*, and Betaproteobacteria are highly increased in T2D sufferers compared to healthy patients and positively correlated with plasma glucose.

A metagenome-wide association study of gut microbiota of T2D Chinese sufferers [94] demonstrated that patients with type 2 diabetes were characterized by a decrease in butyrate-producing bacteria such as *Roseburia* spp. and an increase in various opportunistic pathogens (*Clostridium* spp., *Bacteroides caccae*) as well as an enrichment of other microbial functions conferring sulfate reduction (*Desulfovibrionaceae* spp.).

Gut microbiota interact with various host sensing and signaling pathways, leading to a modulation of the endocrine system, immune responses, nervous system activity, and hence, the predisposition to metabolic diseases. Gut microbiota dysbiosis drives and implies new therapeutic strategies for diabetes and related metabolic diseases [95].

3.2.2. Central Nervous System (CNS)-Related Disorders

The brain and the gut are connected via the gut–brain axis with bidirectional interactions between the central nervous system, the enteric nervous system, and the gastrointestinal tract. These bidirectional interactions enable the brain to influence gastrointestinal functions as well as immune functions.

Alzheimer's and Parkinson's Diseases

Today, over 46 million people live with dementia worldwide [96]. Alzheimer's disease (AD) and Parkinson's disease (PD) are considered the most common forms of dementia in the elderly.

Alzheimer's disease (AD) is a chronic, rapidly progressive neurodegenerative disorder associated with impaired cognition and cerebral accumulation of amyloid-beta peptides. Cattaneo et al. [97] demonstrated that an increase in *Escherichia/Shigella* abundance and a reduction of *E. rectale* abundance are possibly associated with a peripheral inflammatory state in patients with cognitive impairment and brain amyloidosis. Vogt et al. [98] compared gut microbiota composition from patients with and without a diagnosis of AD and revealed a lower microbial diversity compositionally distinct from control-age and sex-matched individuals, with a decrease in Firmicutes and *Bifidobacterium* abundance and an increase in Bacteroidetes abundance in the microbiome of AD participants.

The gut microbiota variations are also involved in the pathogenesis of PD. Hopfner et al. [99] suggested, in agreement with most other studies [100–102], an increase in *Lactobacillaceae* abundance in Parkinson patients compared to healthy controls. Moreover, none of the differences in alpha diversity has been observed between PD cases and controls, whereas beta diversity has been revealed for three bacterial families (*Lactobacillaceae*, *Barnesiellaceae*, and *Enterococcaceae*) [99]. PD is associated with changes in gut microbiota and this gut microbiota dysbiosis may be the mechanism of neuroinflammation that leads to PD pathology [99].

Hepatic Encephalopathy

Hepatic encephalopathy (HE) is a complication of cirrhosis and is defined as a spectrum of neuropsychiatric abnormalities in patients with liver dysfunctions. Bajaj et al. [103] linked the gut microbiota composition with cognition and inflammation in HE. Fecal microbiota of cirrhotics were significantly higher in *Enterobacteriaceae*, *Alcaligenaceae*, and *Fusobacteriaceae* and lower in *Ruminococcaceae* and *Lachnospiraceae* compared with controls [103]; moreover, altered higher levels of *Veillonellaceae* were found in HE patients compared with cirrhotics without HE. In the cirrhosis group, *Alcaligenaceae* and *Porphyromonadaceae* were positively correlated with cognitive impairment. *Fusobacteriaceae*, *Veillonellaceae*, and *Enterobacteriaceae* were positively and *Ruminococcaceae* was negatively related to inflammation. Thus, cirrhosis, especially when complicated with HE, is associated with significant gut microbiota alterations compared with healthy individuals. Specific bacterial families (*Alcaligenaceae*, *Porphyromonadaceae*, and *Enterobacteriaceae*) are strongly associated with cognition and inflammation in HE [103].

Autism Spectrum Disorders

Compared with the gut microbiota of children without ASD, the gut microbiota of children with ASD is less diverse and exhibits lower levels of *Bifidobacterium* and Firmicutes and higher levels of *Lactobacillus*, *Clostridium*, *Bacteroidetes*, *Desulfovibrio*, *Caloramator*, and *Sarcina* [104–107]. A study by Wang et al. [108] showed a decrease in *Bifidobacterium* spp. and mucolytic bacteria *Akkermansia muciniphila* in the gut microbiota of autism subjects compared to control subjects.

Williams et al. [109] found an increase in the Firmicutes-to-Bacteroidetes ratio and a significant increase in *Sutterella* compared to their abundance in controls. These findings demonstrated that gut microbiota dysbiosis has close relationships with gastrointestinal and behavioral manifestations of autism.

Stress

The bidirectional interactions of gut–brain mean that the brain can also alter gut microbiota composition [110]. A model of social disruption among adult mice [111] demonstrated that exposure to stress results in substantial changes in gut microbiota composition: a decrease in *Bacteroides* spp. abundance and an increase in *Clostridium* spp. abundance have been observed in stress-induced mice

relative to controls. The mechanisms by which stress influences gut microbiota composition are unclear but include microbial habitat alterations following stress-induced changes in intestinal mobility and mucin secretion [110,112].

Other studies [62] revealed that chronic psychological stress is reflected in the microbiota composition. Indeed, depression due to chronic stressful life events is associated with an increase in *Enterobacteriaceae*, whereas psychological stress is associated with a reduction in *Lactobacilli* spp. and an increase in *Escherichia coli* and *Pseudomonas* spp.

Gut microbiota variations are closely associated with the onset of these neurological disorders, and the gut bacterial communities may be a target for therapeutic interventions.

4. Conclusions

Each healthy human is provided with unique gut microbiota. Core native microbiota are shaped in early life (4–36 months) by gut maturation developing from enterotype, birth gestational age, type of delivery, methods of milk feeding, weaning period, lifestyle, and dietary and cultural habits. After a child reaches 2–3 years old, a relative stability in gut microbiota composition has been demonstrated. Richness and diversity of gut microbiota shaped in early life characterize a healthy gut microbiota composition. However, this optimal healthy gut microbiota composition is different for each individual.

Throughout life, the richer and more diverse the microbiota, the better they will withstand external threats. Indeed, gut microbiota represent a changing ecosystem that is severely tested by many factors such as unbalanced diet, stress, antibiotic use, or diseases. A healthy host–microorganism balance must be respected in order to optimally perform metabolic and immune functions and prevent disease development. Indeed, disturbances to the delicate host–microbe relationship may disrupt the development of the immune system, which may in turn result in diseases [113]. Although the role of gut microbiota is still poorly understood, the close association between gut microbiota dysbiosis and intestinal and extra-intestinal disorders has been demonstrated. This is the reason why dysbiosis can be considered as a biomarker of such disorders and that the study of gut microbiota balances shall be one of the priorities for future therapies to prevent and treat diseases.

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The human microbiome

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Abstract

Until recently, human microbiology was based on the identification of single microbes, such as bacteria, fungi and viruses, frequently isolated from patients with acute or chronic infections. Novel culture-independent molecular biochemical analyses (genomics, transcriptomics, proteomics, metabolomics) allow today to detect and classify the diverse microorganisms in a given ecosystem (microbiota), such as the gastrointestinal tract, the skin, the airway system, the urogenital tract and others, and to assess all genomes in these ecosystems (microbiome) as well as their gene products. These analyses revealed that each individual has its own microbiota that plays a role in health and disease. In addition, they greatly contributed to the recent advances in the understanding of the pathogenesis of a wide range of human diseases. It is to be expected that these new insights will translate into diagnostic, therapeutic and preventive measures in the context of personalized/precision medicine.

Introduction

The basic aspects of molecular and cell biology are not only integral part of biomedical research but are also translated into patient care. Several global consortia have been launched and in part completed during the last decades. All of them continuously transform basic biomedical research and translate into medical applications and, after evaluation in randomized clinical trials, enter clinical practice with a tremendous potential to advance the diagnosis, treatment and prevention of human diseases.

More than 15 years ago, the international human genome organization (HUGO) project established the complete sequence of the ca. 3 billion base pairs that make up the human genome [1], [2]. In order to utilize these data from the HUGO project for research as well as for clinical applications

[redacted]

and to define the functions of newly identified genes, collectively termed ‘functional genomics’, strategies were developed to globally analyze genomic DNA sequences as well as their cell-, tissue- or organ-specific expression profile. Using chips, so-called 'microarrays', thousands or ten thousands of single-stranded DNA species, reverse transcribed RNA (cDNA) or oligonucleotides of known sequence can provide a global gene (genomics), gene expression (transcriptomics, proteomics) or metabolite (metabolomics) profile (‘signature’) that is characteristic for the disease of individual patients, including its natural course/prognosis and response to therapy.

In 2005 the international haplotype map (HapMap) project was initiated to identify, based on genome-wide association studies (GWAS) in ethnically different populations, single nucleotide polymorphisms (SNPs) and their association with specific human diseases and individual phenotypic characteristics, respectively [3], [4]. Through GWAS an increasing number of gene loci have been identified that are associated with individual (future) phenotypic traits, such as hair or eye color, height, body mass index and others as well as with the disposition to develop a specific disease [3], [4]. Further, genetic variants are associated with the individuals’ response to drug treatment, e.g., to lithium [5]. Overall, GWAS allow an increasingly better understanding of disease pathogenesis and a more accurate assessment of the individual risk to develop a specific disease. Clinically, this may eventually translate into clinical advances in disease prevention, early diagnosis and therapy. It should be cautioned, however, that the contribution of a defined SNP to the risk assessment for a given disease must be weighed against established clinical parameters and needs to be carefully evaluated before entering clinical practice.

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Section snippets

The human microbiome project

The human microbiome project (HMP) was established in 2007 as another global consortium [6], [7], [8], [9], [10]. The HMP and the ‘Metagenomics of the Human Intestinal Tract (Meta-HiT) Consortium Europe’ aim at the sequencing of all microbes (eukaryotes, archaea, bacteria, viruses) that inhabit specific body sites, such as the mouth, throat and airways, stomach and intestine, the urogenital system and the skin, respectively (Fig. 1A). Recent data demonstrate that specific compositions of the …

Conclusions and perspectives

Basic biomedical research has made major advances in recent years and holds the promise to increasingly provide individual diagnostic, preventive as well as therapeutic options for patients with inherited or acquired, malignant or non-malignant diseases. Apart from an increasing number

of host genetic susceptibility loci and environmental factors, the individual microbial community is central for the barrier between microbes and hosts. In particular, the intestinal microbial community is …

Conflict of interests

The author declares no conflict of interest. …

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outlook

Natural immunity

Biodiversity loss and inflammatory diseases are two global megatrends that might be related

We are witnessing two global and deeply worrying trends that, at first glance, seem unrelated. The first trend is the ongoing decline in biodiversity, which is caused by human actions. It could well become the sixth mass extinction of animal and plant species on Earth, comparable in magnitude with the fifth mass extinction at the end of the Cretaceous, 65 million years ago. The second trend is a rapid increase in chronic diseases that are associated with inflammation, especially in developed countries (Fig 1). Inflammation is a key attribute in asthma and allergic diseases, autoimmune diseases and many cancers; even depression has been associated with the presence of inflammatory markers. In this article, we argue that these two phenomena are more closely related than commonly thought: declining biodiversity might actually increase the risk to humanity from chronic diseases and thereby cause a major public health problem.

We thereby extend the hygiene and microbial deprivation hypotheses to a biodiversity hypothesis, with inevitable consequences for public health

The underappreciated link between biodiversity and human health are microbes, which inhabit all ecosystems, including the human body. Although microbial life on Earth as such is not threatened—unlike many plant and animal species—the diversity and abundance of microorganisms in affluent urban environments has clearly declined (Alenius *et al*, 2008), which raises intriguing questions. What are the effects of the loss of biodiversity of plants, animals and their habitats on the environmental microbiota? What is the relationship of the microbiota living on our skin, in our respiratory system and in our gut, with the environmental microbiota? What are the effects of any changes in human bacterial communities on human health?

Our proposal would expand the 'hygiene hypothesis', which posits that environments rich in microbial diversity confer protection against allergic and autoimmune diseases (Rook, 2009). While the hygiene hypothesis mainly focuses on microbes in the home, in food and drinking water and on domestic animals, we believe that it should include our living environment in general. We thereby extend the hygiene and microbial deprivation hypotheses to a biodiversity hypothesis, with inevitable consequences for public health.

Biodiversity means, by definition, "the variability among living organisms from all sources, including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (www.biodiv.org/convention/). In practice, the most pertinent elements of biodiversity are genetically diverse populations of many species, including cultivated plants and domesticated animals; the size and the state of natural habitats; and the functioning of ecosystems. Although the Convention of Biological Diversity is primarily concerned with plants and animals, biodiversity includes microorganisms, which are less visible but which comprise the bulk of living matter on Earth.

The United Nations' International Year of Biodiversity in 2010 was supposed to be the turning point for biodiversity loss. Yet, a recent report confirms that the rate of decline shows no signs of slowing down; the various pressures on biodiversity continue to increase (Butchart *et al*, 2010). On the basis of figures from the Millennium Ecosystem Assessment, the pre-human background rate of species extinction, calculated from the fossil record, is between 0.001% and 0.01% of species per 100 years. The current rate is approximately 1% and is increasing: future projections estimate that 20–30% of species will become extinct within the next 100 years. This figure might seem high, but it is consistent with the most recent data about threatened species (www.iucnredlist.org/). Overall, one-third of the 56,000 animal and plant species that are sufficiently well known to allow the evaluation of their status are threatened. The main cause for this dramatic loss of biodiversity is major changes in land use, mostly driven by the expansion of the human population and the ensuing destruction of natural habitats.

Overall, one-third of the 56,000 animal and plant species that are sufficiently well known to allow the evaluation of their status are threatened

The loss of natural habitats, ecosystems and biodiversity has drastic consequences for human health. An expanding body of evidence demonstrates how natural environments are vitally important to physical and mental health. For instance, a recent study reported an inverse association between physician-diagnosed health and the proportion of green space in the patients' environment (Maas *et al*, 2009). Nature, and forests in particular, have substantial potential to improve human health; the International Union of Forest Research Organizations (IUFRO) has launched a task

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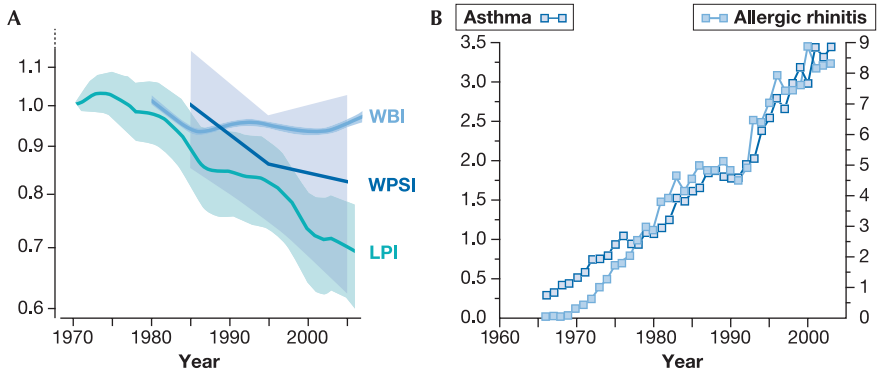


Fig 1 | Two global megatrends in biodiversity and public health. (**A**) Declining biodiversity since 1970 as measured by three indices. LPI, Living Planet Index; WBI, World Bird Index; WPSI, Waterbird Population Status Index (Butchart *et al*, 2010). (**B**) Increasing trends in the prevalence of inflammatory diseases. Asthma and allergic rhinitis among military conscripts from 1966 to 2003 (Latvala *et al*, 2005) are shown as an example.

Table 1 | Reduced diversity and/or altered composition of microorganisms in the gut and respiratory tract is associated with chronic inflammatory diseases

Disease	Evidence from	Reference
Gut		
Asthma/allergy	Humans	Sjögren *et al*, 2009
Type 1 diabetes	Mice	Wen *et al*, 2008
Inflammatory bowel disease	Humans, mice	Round & Mazmanian, 2009
Obesity	Humans, mice	Turnbaugh *et al*, 2009
Behavioural changes	Mice	Bienenstock & Collins, 2010
Respiratory tract		
Asthma, chronic obstructive pulmonary disease	Humans	Hilty *et al*, 2010

force on Forests and Human Health to investigate further this concept (www.iufro.org/science/task-forces/forests-trees-humans/; www.forhealth.fi). Such associations between nature and health are well recognized, but we need more data and better understanding of the relevant mechanisms at the cellular and molecular levels.

The processes that link human health and environmental changes are multifaceted, complex and difficult to examine experimentally, but it is clear that microorganisms have a key role. Commensals inhabiting our skin and mucosae are not passive bystanders or transient passengers, but active participants in the development and maintenance of barrier function and immunological tolerance in humans, and it is becoming increasingly clear that human health depends on both commensal and environmental microorganisms. This microbial zoo includes bacteria, fungi, viruses and microscopic protozoans, although hardly any data are available on the roles of the latter.

The bacteria population in the human gut has a high diversity at the genus and species level, but the community is dominated by two phyla, Firmicutes and Bacteroidetes, and to a lesser extent by Acinobacteria and Proteobacteria (Turnbaugh *et al*, 2009). Recent metagenomic data indicate that each human harbours at least 160 bacterial species, which are partly shared with other individuals. The total number of bacterial species identified in a sample of 124 Europeans was 1,000–1,150 (Qin *et al*, 2010), suggesting a rather distinct individual composition of the flora.

The processes that link human health and environmental changes are multifaceted, complex and difficult to examine experimentally, but it is clear that microorganisms have a key role

It is well known that reduced diversity and composition changes of the gut microbial community are associated with allergic disease (Sjögren *et al*, 2009); recent studies indicate similar associations with other inflammatory conditions (Table 1). The evidence from mice and humans indicates that some common members of the normal microbiota have a special role in maintaining homeostasis and health (reviewed by Round & Mazmanian, 2009; Fig 2). Changes in the indigenous microbiota might therefore readily translate into disease.

Similarly to the gut microbiota, bacterial communities on our skin are a complex ecosystem with various lines of cells that can communicate with each other and with host cells. Its members come from the same four phyla as in the gut, although with different relative abundances, as Gram-positive Actinobacteria and Firmicutes dominate (70–80%). Each body site harbours a characteristic microbiota with relatively low temporal variation (Grice *et al*, 2009; Costello *et al*, 2009). Metagenomic studies have revealed that the diversity of bacterial communities on the skin is comparable with the gut microbiota (Qin *et al*, 2010; Fierer *et al*, 2008), implying that the skin microbiota also has an important role in the immune system. The skin community, like the gut community, includes both transient and permanent members (Grice *et al*, 2009), suggesting that at least a part of the community is in dynamic interaction with the environment. Most research has been carried out and published on the gut flora and its role in health and disease, but ongoing metagenomic projects might well reveal a significant role for these other microbiota.

The role of microorganisms is fundamental for immunological tolerance and tissue integrity. Although the cause and effect are not entirely clear, literature on the development of epithelial cell tolerance and homeostasis (von Hertzen *et al*, 2011) and experiments that involve the transfer of gut microbiota (Turnbaugh *et al*, 2006; Wen *et al*, 2008) show that altered environmental microbiota and reduced Toll-like receptor signalling cause immune dysfunction, which enhances the colonization and growth of a different microbiota. This creates a self-perpetuating cycle that pushes the host–microbe system towards an 'unhealthy' state.

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The protective mechanisms against inflammatory diseases crucially involve activation of innate and regulatory networks by continuous exposure to microbes through the skin, gut and respiratory tract; in fact, humans have evolved over millennia to coexist with microorganisms that do not elicit immune responses, but rather induce immunoregulatory circuits. Thus, reduced diversity and exposure to these microorganisms might now lead to failure to terminate and restore inappropriate inflammatory responses (Rook, 2009). Two major discoveries in immunology—the regulatory network and the Toll-like receptor system—have fundamentally improved our understanding of the role of commensal and saprophytic microbes in health and disease. The interaction of microbes with their specific receptors on and in immune cells is necessary for the development and maintenance of epithelial cell integrity, tolerance and tissue repair. In the absence of these microbial stimuli, the immunoregulatory circuits, including regulatory cytokines interleukin-10 and transforming growth factor-β, regulatory dendritic cells and regulatory T (T_{REG}) cells, are no longer adequately induced. An inflammatory milieu, in turn, might enhance the conversion of T_{REG} cells to inflammatory T_H17 cells (von Hertzen *et al*, 2011) and enrich bacteria that tolerate inflammatory mediators in the microbiota, thereby creating a self-perpetuating system (Fig 3). These molecular findings further support the hygiene hypothesis, which states that a sedentary lifestyle in affluent urban environments does not provide adequate microbial exposure for the development of a 'healthy' microbiota.

Epigenetic mechanisms have also received much attention during the past few years as a possible explanation of how environmental exposure modulates the immune system. Environmental factors evidently have key roles in activating or silencing genes by altering DNA and histone methylation, histone acetylation and chromatin structure, which might modify disease susceptibility in individuals. Vuillermin *et al* (2009) suggest that microbial exposure is linked with demethylation (activation) of the interferon (*IFN*)-γ gene in naive T cells; thus, microbial deprivation in early life is associated with persistent methylation (silencing) of the *IFN*-γ gene, resulting in reduced IFN-γ production and increased risk for allergic diseases. In general, microbe-rich environments induce both proinflammatory and regulatory circuits early in life (Schaub *et al*, 2009), indicating an early activation of the relevant genes. These observations call for more research on the role of microbial stimuli in the epigenetic modulation of T cells, particularly T_{REG}-cell function.

Although early life is important for epigenetic modulation, significant changes might occur later, as Fraga *et al* (2005) showed in a comprehensive study of monozygotic twins. While the twins appeared to be epigenetically indistinguishable in early life, older monozygotic twins who had different lifestyles and had spent less of their lives together had substantial differences in the overall content and genomic distribution of methylation and histone acetylation—which probably contribute to discordance in disease susceptibility.

…humans have evolved over millennia to coexist with microorganisms that do not elicit immune responses, but rather induce immunoregulatory circuits

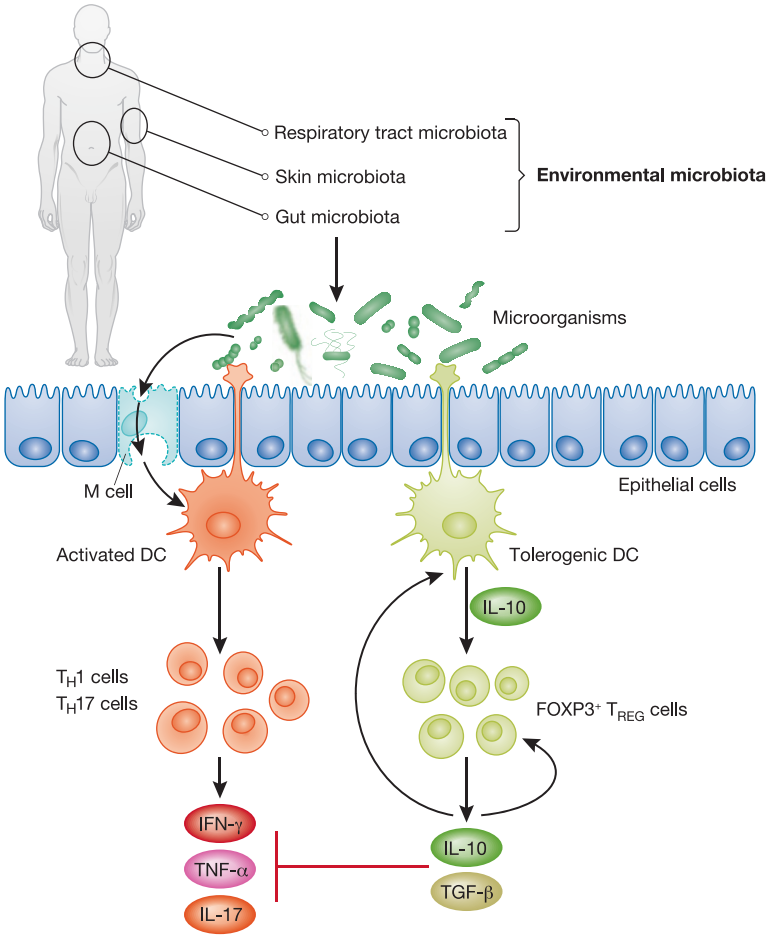


Fig 2 | Epithelial cells in the respiratory tract, skin and gut are constantly exposed to both environmental and indigenous microorganisms. In addition to active transport of antigens by specialized gut epithelial cells (M cells) and their constant sampling by dendritic cells (DCs), epithelial cells recognize bacterial antigens directly through Toll-like receptors. Similarly to mucosal epithelial cells, skin epidermal cells, keratinocytes and Langerhans cells, also express a broad range of Toll-like receptors. In steady-state conditions, T_{REG} cells, through continuous stimulation of epithelial and innate immune cells, prevent inappropriate inflammatory responses by IL-10/TGF-β production. Microorganisms might also be involved in the epigenetic modulation of immune responses. FOXP3, forkhead box P3; IL, interleukin; IFN-γ, interferon-γ; TGF-β, transforming growtth factor-β; TNF-α, tumour necrosis factor-α.

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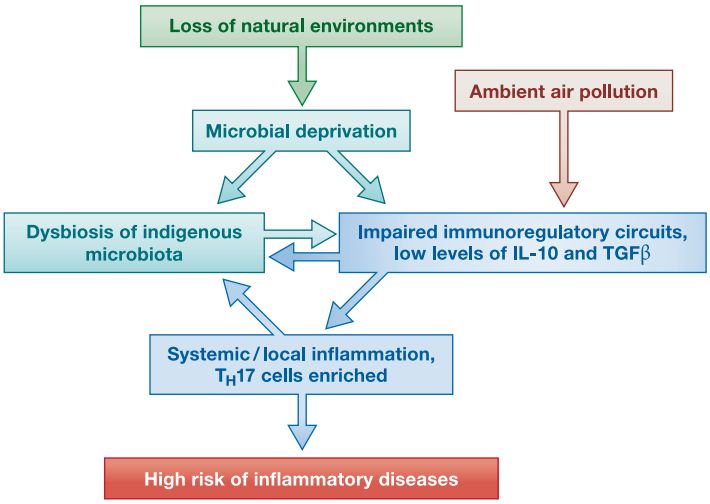


Fig 3 | In the absence of sufficient microbial stimuli, immunoregulatory circuits are not induced adequately resulting in low levels of interleukin (IL)-10/transforming growth factor (TGF)-β. An inflammatory milieu, in turn, enhances the conversion of T_{REG} cells to T_H17 cells and favours the enrichment of bacteria in the gut (and other microbiota) that tolerate inflammatory mediators, creating a self-perpetuating system. Ambient air pollution might act in synergy and further strengthen immune dysregulation by inactivating FOXP3$^+$ T_{REG} cells by epigenetic mechanisms. Together, these factors probably contribute to the increase in inflammatory diseases in developed countries.

Perhaps the strongest evidence for the idea that lifestyle and environmental factors modulate immune regulation comes from epidemiological studies on immigrants. Individuals who move from areas with a low prevalence of chronic diseases to an area with a high prevalence often have a good health status after arrival: the 'healthy immigrant effect'. However, their health eventually declines to the same level as the native population or worse. These changes seem to occur within 10 years after arrival, but are often most dramatic in recently arrived individuals (Newbold, 2005); this phenomenon is not restricted to young people but occurs also in adults (Kalyoncu & Stålenheim, 1992). This immunomodulation by cultural adaptation—which goes together with changes in disease susceptibility—seems to be a universal phenomenon for various inflammatory diseases, including asthma and allergies (Grüber *et al*, 2002; Kalyoncu & Stålenheim, 1992), autoimmune diseases (Bodansky *et al*, 1992), obesity and type 2 diabetes (Creatore *et al*, 2010), depression (Casimir *et al*, 2010) and cancer (Pinheiro *et al*, 2009). The disease spectrum is similar to that associated with altered gut microbiota, as discussed above.

The loss of biodiversity and disappearance of natural habitats pose a serious threat to humankind because they impair many essential ecosystem services—one of which is the role of environmental microbiota in enhancing human health. Living in dense urban environments might therefore lead to an 'immune adaptation syndrome'—that is, the inability of the immune system to adapt to microbe-poor environments—in a large part of the population. At the population level, changes in disease prevalence are slow to become apparent—the allergy problem, for instance, became visible in the mid-1800s even when people had been living in cities for a long time. At the individual level, immune disorders often start early in life, last for a long time, might cause disability and require continuous medical treatment, which creates a considerable burden for both patients and society.

Within the next 30 years, two-thirds of the population in developing countries and almost 85% of the population in developed countries will live in urban areas with little green space

People in affluent societies have both adapted their urban environment and have themselves adapted to it in order to balance their immune system. The creation of large parks and green belts in cities or local recreation areas certainly improve the mental and physical well-being of city dwellers. It is, however, increasingly difficult to create 'immune-friendly' green areas in the rapidly growing megacities. As the global population continues to grow, resources become increasingly scarce, and there is simply less vacant space. Within the next 30 years, two-thirds of the population in developing countries and almost 85% of the population in developed countries will live in urban areas with little green space (World Urbanization Prospects: The 2007 Revision Population Database; http://esa.un.org/unup/). Urbanization and densification continue despite the accumulating data showing that natural environments are associated with better physical and mental health.

The hypothesis that we propose—biodiversity loss leads to immune dysfunction and disease—has numerous societal and public health implications that are increasingly apparent in the developed world and will have a major impact on developing countries in the near future. Two independent lines of research—metagenomic studies of the microbiota in the gut and other sites, and immigrant studies—support our idea that inflammatory diseases characteristic of urban life in affluent countries are associated with changes in the environmental and commensal microbiota. We have already lost a huge amount of natural environments in the industrialized and developed countries and thereby depleted their biodiversity; if biodiversity loss continues unabated, the prospects for public health might indeed be bleak. The growing burden of inflammatory diseases might also enter a vicious cycle if the response is to reduce further our exposure to natural environments. Biodiversity loss works in the same direction, as it diminishes opportunities for outdoor activities and therefore encourages a sedentary lifestyle.

Chronic inflammatory disorders can be added to the long list of reasons of why we should care for the diversity of animal, plant and microbial life on Earth. We need to consider measures that not only preserve the natural environment but also reconnect us with nature. We need to preserve our connection to the soil and green spaces, we

…if biodiversity loss continues unabated, the prospects for public health might indeed be bleak

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need to expose our children to natural environments, and we need to change food production and transportation, to mention just a few measures. Above all, however, we need to urgently stop the ongoing species extinction—as humans cause it, they also have the power to stop it. Even if molecular biology and biomedical research might eventually develop immune-stimulating treatments to address the burden of chronic inflammatory disease, these will be only paltry substitutes of nature.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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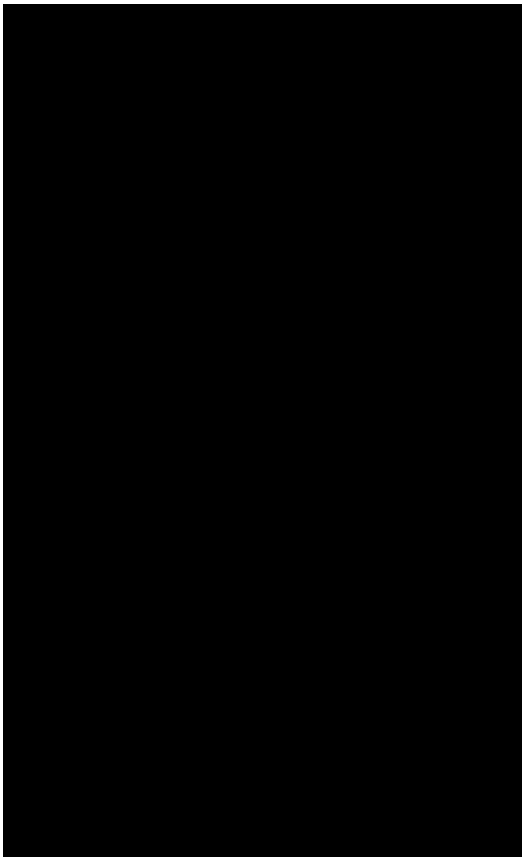
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PERSPECTIVE

Regulation of the immune system by biodiversity from the natural environment: An ecosystem service essential to health

[redacted]

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Edited [redacted]

Epidemiological studies suggest that living close to the natural environment is associated with long-term health benefits including reduced death rates, reduced cardiovascular disease, and reduced psychiatric problems. This is often attributed to psychological mechanisms, boosted by exercise, social interactions, and sunlight. Compared with urban environments, exposure to green spaces does indeed trigger rapid psychological, physiological, and endocrinological effects. However, there is little evidence that these rapid transient effects cause long-term health benefits or even that they are a specific property of natural environments. Meanwhile, the illnesses that are increasing in high-income countries are associated with failing immunoregulation and poorly regulated inflammatory responses, manifested as chronically raised C-reactive protein and proinflammatory cytokines. This failure of immunoregulation is partly attributable to a lack of exposure to organisms ("Old Friends") from mankind's evolutionary past that needed to be tolerated and therefore evolved roles in driving immunoregulatory mechanisms. Some Old Friends (such as helminths and infections picked up at birth that established carrier states) are almost eliminated from the urban environment. This increases our dependence on Old Friends derived from our mothers, other people, animals, and the environment. It is suggested that the requirement for microbial input from the environment to drive immunoregulation is a major component of the beneficial effect of green space, and a neglected ecosystem service that is essential for our well-being. This insight will allow green spaces to be designed to optimize health benefits and will provide impetus from health systems for the preservation of ecosystem biodiversity.

Numerous studies demonstrate that living close to the natural rural or coastal environment, often denoted "green space or "blue space," respectively, is beneficial for human health. It reduces overall mortality, cardiovascular disease, and depressive symptoms and increases subjective feelings of well-being (1–8). The beneficial effects are particularly prominent in individuals of low socioeconomic status (1–3, 8). It is often suggested that the mechanism of this effect is psychological. Looking at green spaces or walking in parkland or forests cause rapid psychological and physiological changes that can be demonstrated not only by psychological testing (4) but also by mobile elecroencephalograms (5) and by measurements of cerebral blood flow, various cardiac parameters, blood pressure, and salivary cortisol (6, 7). Even looking at the natural environment as images or through a window is said to have beneficial effects (9). Some authors explain this from an evolutionary perspective (10). The relaxation and satisfaction derived from the natural environment might represent the equivalent of "habitat selection" in other species (11). As shown recently by analyzing carbon isotopes in tooth enamel, from as early as 3–4 Mya, hominins were evolving in wooded grassland (12) and followed rivers and coastlines or settled near lakes. Thus, humans will have evolved to obtain psychological rewards from approaching these ideal hunter-gatherer habitats (10).

This psychological explanation is often supplemented by other factors: social interactions, exercise, and sunlight. For example, the natural environment might promote social interactions and a sense of community (13) when the natural environment is an important contributor to the social capital of the individual (14). Similarly green spaces sometimes encourage physical activity (15), although city-dwellers can walk to most resources and tend to do so, whereas individuals living in leafy suburbs are often forced to use their cars to get anywhere at all, so exercise can paradoxically decrease (16, 17). Sunlight is thought to counteract seasonal affective disorder (SAD) and has been used to treat tuberculosis and heal infected wounds (18, 19).

Although all these factors may contribute to the beneficial effects, there are two major uncertainties about the psychological component. First, there is the issue of specificity. Most psychological studies fail to include appropriate controls. It is not sufficient to compare exposure to a city street with exposure to a green space. Would any suitably relaxing environment—a quiet comfortable café, or a cinema showing a feel-good film in the urban environment—have the same psychological effects as green space when tested in comparison with a busy city street? [The other suggested benefits—social interaction, exercise, and sunlight—are clearly not specific for green space. Social capital usually derives from urban social interactions, and it has not been possible, using currently available data, to determine whether exercise taken in a green space is more beneficial than similar exercise taken in a city gym (20): there are undoubtedly health effects of exercise that do not depend on green space (21)].

The second uncertainty about the psychological explanation is the absence of evidence that the measurable rapid short-term psychological and physiological changes that follow exposure to natural environments (whether specific for such environments or not) translate into long-term health benefits. In other words, are these short-term psychological effects related in any way to the suggested health benefits of living close to green space for prolonged periods (reduced mortality, cardiovascular disease, chronic inflammatory disorders, and depression) (1, 2, 22, 23), or are they a separate transient phenomenon?

Summarizing the previous paragraphs, there is suggestive evidence that living close to the natural environment (defined here as nonbuilt, including gardens and agricultural land) has long-term health benefits (1, 2, 8).

Author [redacted]

The author declares no conflict of interest.

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These benefits might be an additive consequence of several effects—an evolved psychological need, plus perhaps exercise, sunlight, and social interactions—but there are no conclusive data. This issue is crucially important because urban planners need to know whether urban green space is really the best way to achieve the beneficial effects, and assuming that it is, they then need to know the mechanism so that the health advantage derived from green spaces can be optimized. We suggest here that humans do indeed have an evolutionarily predetermined need for exposure to the natural environment, but that this has two distinct components. There is an immunological component that runs in parallel with the psychological one discussed above. This discussion is needed because the field is split into two distinct trains of thought that involve different aspects of our physiology (the brain and the immune system) and different scientific and medical disciplines. We hope here to break down these interdisciplinary barriers and show that these two pathways are likely to work together in ways that can usefully benefit urban planning for human well-being.

Hygiene Hypothesis and the "Old Friends" Mechanism

The high-income countries are undergoing massive increases in chronic inflammatory disorders (24–27). The cause is at least partly a failure of immunoregulation, so that the immune system is attacking inappropriate targets, such as self, harmless airborne antigens (allergens) and gut contents. At birth the immune system is like a computer (anatomical structures) that contains programs (genetics) but almost no data in terms of knowledge of molecular structures in the environment into which the child is born. It has some knowledge of self, acquired as lymphocytes mature in the thymus, and minimal knowledge of the outside world, transferred from the mother across the placenta. After birth, it needs microbial exposures to provide teaching inputs for several crucial reasons. First, exposure to a broad biodiversity of organisms builds up memory of diverse molecular structures that accelerates subsequent rapid recognition of novel dangerous organisms (28, 29). Second, microbial components taken up systemically from the gut maintain an essential background level of activation of the innate immune system (30). Third, and most important in the current context, the system needs to develop a network of regulatory pathways and regulatory T cells (Tregs) that stop inappropriate immune attacks on (*i*) self; (*ii*) harmless allergens; and (*iii*) gut contents (Fig. 1). If immunoregulation fails to stop immune attack on any of these categories of forbidden targets, the consequences are (*i*) autoimmune diseases such as multiple sclerosis; (*ii*) allergic disorders such as hay fever and atopic asthma; and (*iii*) inflammatory bowel diseases such as ulcerative colitis and Crohn's disease (Fig. 1).

Finally, the immunoregulatory systems must also turn off inflammatory responses completely when they are not needed. A failure to do this is regularly seen in high-income countries where persistently raised levels of C-reactive protein (CRP) are common (discussed in ref. 31). Persistently raised inflammatory mediators lead to increased risk of cardiovascular disease (32) and depression (27, 33, 34). In contrast, a longitudinal study of adults in a rural low-income country where there is exposure to high microbial burdens in childhood showed that they were able to shut off the inflammatory response when there was no need for it (31). More work is needed to discover whether the same is true in other low-income settings, whether biomass or biodiversity was more important, and whether the effect was attributable to bacteria, fungi, protozoa, helminths, or other organisms. Fig. 2 illustrates some of the categories of organisms (Old Friends) implicated in driving the immunoregulatory mechanisms (reviewed and referenced in ref. 35). The crucial point is that all these organisms needed to be tolerated. Some were part of our physiology (human microbiota). Others were harmless but inevitably contaminating food and water (environmental microbiota). Similarly, there were carrier states due to organisms picked up soon after birth and helminths that persist for life. Helminthic parasites needed to be tolerated because, although not always harmless, once they were established in the host, any effort by the immune system to eliminate them was futile and merely caused tissue damage such as elephantiasis (36). Thus, helminths are powerfully immunoregulatory and act as Treg adjuvants. For example, when patients suffering from early relapsing multiple sclerosis (MS) become infected with helminths, the disease stops progressing, and circulating myelin-recognizing Tregs appear in the peripheral blood (37, 38), an exciting observation that has led to formal clinical trials (39). This view is now well supported by experimental data and molecular mechanisms. Old Friends can be shown to drive immunoregulation and to block or treat models of allergies, autoimmune disease, and inflammatory bowel disease (40–42). Some Old Friends (including members of the human gut microbiota such as *Bacteroides fragilis*) or molecules that they secrete are known to specifically expand Treg populations (42–45) or to cause dendritic cells (DCs) to switch to regulatory DCs that preferentially drive immunoregulation (46). However, it is important to remember that the gut is not the only site where immunoregulation can be induced by macro- and microorganisms. Helminths such as blood nematodes that never enter the gut are powerfully immunoregulatory (36), and recent data implicate the skin and airways also (29, 47).

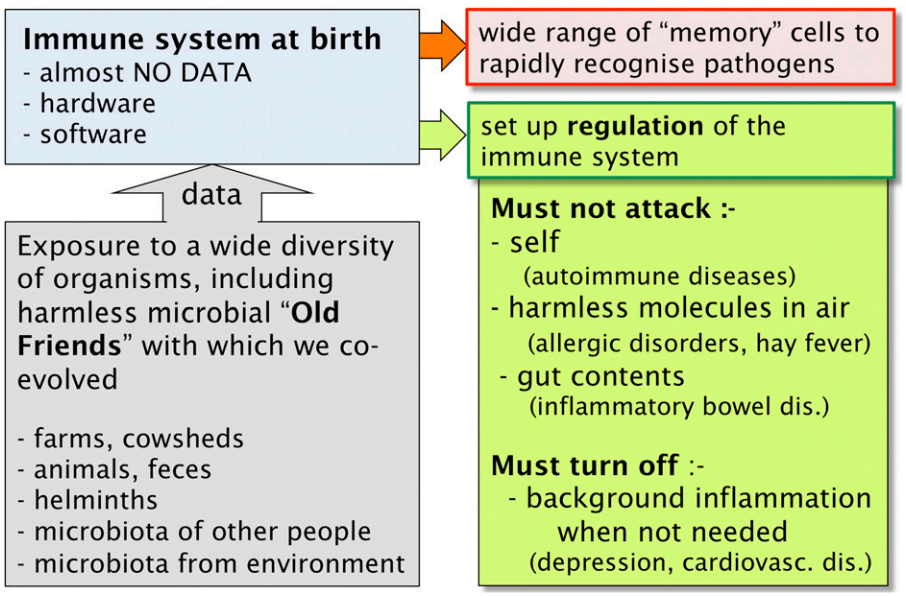


Fig. 1. The immune system does not develop normally in the absence of microbial inputs. In addition to a repertoire of potential effector cells, the system also requires regulatory circuits that inhibit damaging responses to inappropriate targets (such as self, trivial antigens in air, and gut contents) and that terminate inflammatory responses that are no longer needed. The disease groups that occur when immunoregulation fails are indicated in parentheses.

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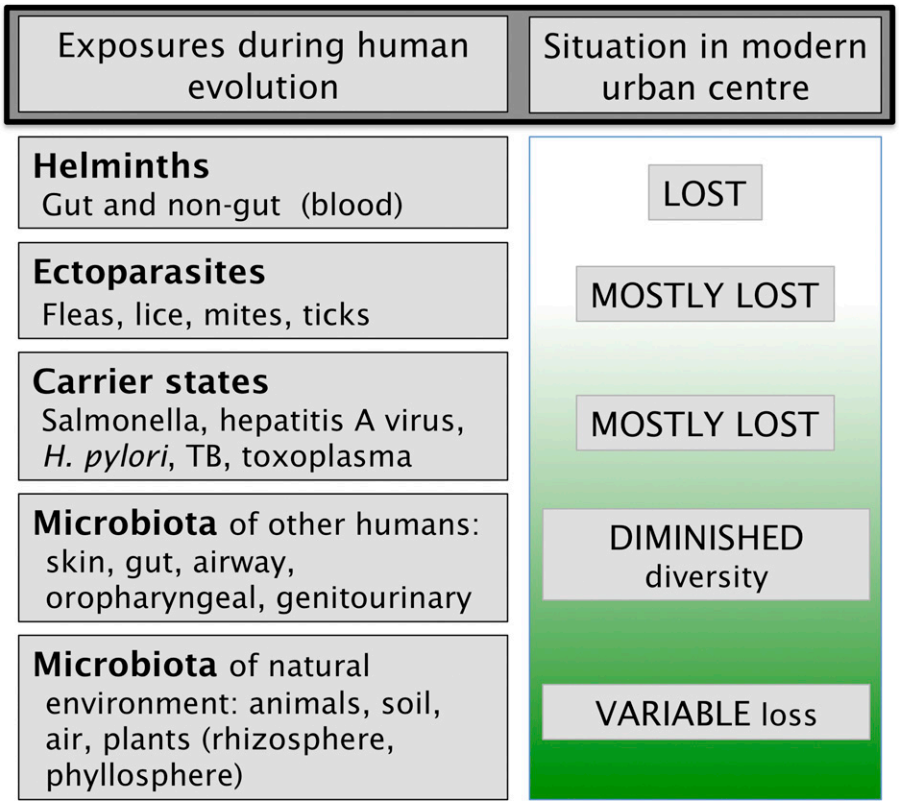


Fig. 2. A simple classification of organisms and parasites with which humans coevolved and that have been implicated by epidemiology or experimental models in the modulation of immunoregulation (although those listed as carrier states might be biomarkers of exchange of microbiota with other humans). The modern urban environment eliminates the first three categories, thus increasing our dependence on microbiota from other humans and from the natural environment.

In summary, it is now understood that the various classes of organism (Fig. 2) that had to be tolerated were entrusted by evolutionary processes with the role of setting up the immunoregulatory mechanisms and Treg populations. If this process fails, we develop susceptibility to chronic inflammatory diseases (24, 26, 37, 48), cardiovascular disease (49, 50), and some forms of inflammation-associated depression (27, 33, 51). This concept constitutes the Darwinian reformulation of the hygiene hypothesis in which the emphasis is on lifestyle changes that reduce our exposure to these immunoregulation-inducing Old Friends.

Progressive Loss of Microbial Inputs

Fig. 2 points out that in modern high-income societies, we have lost many of these categories of immunoregulatory Old Friends, so we are now much more dependent on the immunoregulation-inducing effects of the microbiota of other humans and on organisms from the natural environment. These sources of biodiversity are all that remain. However, increasing trends toward agricultural monoculture are likely to decrease rural microbial biodiversity because each crop is associated with strikingly different populations of bacteria, archaea, fungi, protozoa, nematodes, etc. (52). Similarly, the chronic inflammatory disorders that have risen strikingly in prevalence in developed high-income countries are usually found to be still more common in urban environments from which the immunoregulatory Old Friends are essentially absent (Fig. 2). This urban increase is true for allergies (53, 54), inflammatory bowel disease (55), and for autoimmune diseases such as MS (56–58). These urban-rural differences are equally obvious in psychiatric disorders (59). For example, a meta-analysis of high-quality studies performed in high-income countries since 1985 found that the prevalence of depression in urban areas was 39% higher than in rural areas. Similarly, the prevalence of anxiety disorders was 21% higher in urban than in rural areas (60), although a small minority of studies fails to find this urban-rural difference (61). Peen and colleagues also noted an increased urban prevalence of psychiatric disorders in general (38% more in urban communities) (60), and this is strikingly true for schizophrenia (62) and autism (63)—both of which involve an inflammatory component (64). It is usually suggested that these results are explained by greater stressfulness of urban life, or poor urban social networks, but data to establish these explanations are not provided (59). Meanwhile, an increasingly strong case can be made for the involvement of inflammation, secondary to failing immunoregulation in urban environments (27).

It should, however, be noted that not all studies find higher disease prevalences in urban rather than in rural environments. A study performed in the United States found no link between city-level greenness and heart disease and found greater overall mortality in greener cities, possibly attributable to greater car use (17). However, this city-level study did not provide data at the level of the proximity of the individual to green space. Moreover, it combined data from cities in cool wet environments with data from deserts, and apart from heart disease, did not document the chronic inflammatory disorders that are influenced by the immunological mechanisms discussed here.

Another situation that leads to a loss of exposure to microbial biodiversity is immigration from a developing country to a high-income urban center. This migration leads to rapid loss of the first three categories of organism shown in Fig. 2. In such immigrant populations, there are large increases in autoimmunity (27, 65–69), inflammatory bowel disease (55, 70, 71), depression (27, 72, 73), and allergic disorders (74–77). For allergic disorders, this has been rigorously documented for children adopted into Sweden from low/middle-income countries (75), for Mexican immigrants to the United States (76), and for immigrants to Israel from the former Soviet Union or Ethiopia (77).

Natural Environment and Immunoregulation

Some aspects of the Old Friends mechanism (such as immunoregulatory effects of helminths) are clearly not directly relevant to the green space phenomenon in high-income countries. Their absence merely increases our dependence on immunoregulation-inducing exposures from elsewhere, and the focus of this paper is the natural environment. Observations linking exposure to green environments and agriculture to protection from illness were made as early as the 19th century by Blackley who noticed that hay fever was rare among farmers (78). This observation has now been confirmed in many countries using rigorous epidemiological methods (54, 79). Moreover exposure to farms also protects from juvenile forms of inflammatory bowel disease (80). In agreement with the theme of this paper, recent studies indicate that the mechanism of this protection from allergic disorders involves exposure to microbial biodiversity (81).

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Mattress dust was screened for bacterial DNA (48) and in a separate study samples of settled dust from children's rooms were gathered with electrostatic dust samplers and evaluated for bacterial and fungal taxa using culture techniques. In both studies, the diversity of microorganisms found was inversely related to the risk of asthma (48). Some of the microorganisms found in dust collected from protective farms have been shown to exert potent antiallergic effects in animal models (82–84) and constitute environmental Old Friends. Recently Hanski and colleagues recorded the skin microbiota as well as allergic sensitization to common allergens in an ecologically mixed area of Finland. Subjects living close to agricultural land rather than urban agglomerations had higher generic diversity of proteobacteria in their skin microbiota and less atopic sensitization (47). Similarly, a genetically homogeneous population living in Karelia is partitioned between Finland and Russia. In Finnish Karelia, the prevalence of type 1 diabetes is sixfold higher and childhood atopy is fourfold higher than in Russian Karelia. These differences are associated with strikingly different microbial populations in the home, with much greater diversity and many more animal-associated strains in Russian homes and more plant-associated species in the Finnish homes (85, 86). We cannot at this stage know whether the crucial factor is biodiversity, total microbial biomass, animal-derived organisms, or organisms from other environmental sources.

Microbial Diversity and the Air

What are the microbial exposures that result from proximity to the natural environment or farms or that fall onto settle plates in a child's bedroom? First, the air itself contains large numbers of microorganisms, some of which may actively metabolize and replicate in the air (87). Particulate matter in the air such as pollen carries a load of bacteria (88). Many airborne particles are more than 5 μm and will therefore be deposited in the upper airways, so that after being carried up the trachea by the action of cilia, they will be swallowed. Therefore, airborne microorganisms end up on the skin, in the airways, and in the gut where they modulate the immune system.

When total numbers of organisms in air were counted (i.e., not only the cultivable ones) levels of $10^5/m^3$ or more were regularly encountered over a grassy field on clear sunny days, and estimates approaching $10^6/m^3$ have been reported above shrubs and some grasslands (reviewed in ref. 89). The air in facilities housing agricultural animals can contain still higher numbers, reaching 10^7–10^8 archaea and bacteria/m^3 (90). Aerosols collected in Texas contained at least 1,800 different bacterial types, representing diversity comparable to that seen in some soils (91). Indeed bacteria commonly found in soil and water are abundant in outdoor air (92, 93). Recent samples from the upper troposphere contained variable proportions of bacteria thought to originate from soil, feces, fresh water, or the sea (94). Thus, blue space is another source of microbial biodiversity. Living by the coast does yield health benefits (8), and marine spray is a rich source of usually harmless microorganisms (95, 96). Interestingly, an organism that is not harmless provides proof of physiologically significant levels of intake of marine aerosols and their contained life forms. There is rapid (<1 h) onset of symptoms of brevetoxin poisoning while walking on beaches during algal blooms (97) and parallel increases in pulmonary problems at some distance inland from such beaches (98).

The microbial diversity that we encounter in the natural environment comes mostly from the soil and from plants and from any animals that are present (89, 92, 93). The microbiota of the soil has huge complexity, and is only now beginning to be explored in a global effort (www.earthmicrobiome.org/) (99). Our ignorance of what is out there remains profound, and these gaps in our understanding have been referred to as microbial "dark matter" (100). Tens of thousands of microbial species are associated with the rhizosphere (the below ground microbial habitat constituted by plant root systems) and the phyllosphere (above ground microbial habitats provided by plants). The crucial point is that plants are able to shape the microbiota of their rhizospheres (101). Thus, the nature of the vegetation in a green space will directly modulate the microbiota present in the soil, rhizosphere, and phyllosphere (102) and indirectly modulate the microbiota available from coexisting animal life. The nature, quantity, and diversity of microorganisms present is strikingly affected by agricultural practices (52), and it is likely that the modern trend toward vast areas of monoculture will reduce that diversity and further decrease exposure to immunoregulation-inducing organisms in wealthy countries.

Microbiota from Animals and Other People

The issue of microbiota derived from animals deserves further comment. The microbiota in dust from households with dogs is significantly richer and more diverse than that found in homes without pets (93, 103). This observation is interesting because exposure to pets, particularly dogs, in early life, protects against allergic sensitization and allergic disorders (104, 105). Moreover dogs were domesticated between 33,000 and 11,000 y ago, so humans have coevolved with dog microbiota for many millennia (106). Considered together with the protective effects of early exposure to cowsheds (79), other animal-derived strains (85), or animal feces (31), this might suggest that animals are a particularly important component of the natural environment. However, other humans are also relevant in this context. Some consider that social interactions are an important consequence of access to the natural environment, and it may be true that such interactions promote well-being by boosting social capital (13, 14), but they will also increase the diversity of organisms to which the individual is exposed. Teammates playing a contact sport tended to share a microbiota, but this converged with that of the opposing team after a match (107). Similarly cohabiting individuals tend to share microbiota (108). Interestingly people tend to share even more microbiota with their dogs (108), increasing exposure to the dog-associated microbial diversity mentioned above (93, 103). In sharp contrast, elderly people shut up in care homes with little variety in human contact (and little exposure to the natural environment) have diminished gut microbiota diversity that correlates with poor health outcomes and increased levels of biomarkers of inflammation such as IL-6 (109).

Microbiota of the Built Environment

The airborne microbiota of buildings is still poorly defined but can be different from that of the natural environment. The phylogenetic diversity of the airborne bacteria in mechanically ventilated rooms was lower than that seen in rooms ventilated via open windows or in the outdoor air itself (92, 93). Similarly the organisms derived from soil and water were abundant in samples of outdoor air but rare or absent from the indoor samples, which were dominated by organisms related to human pathogens and commensals (92). Air in cities tends to contain more particulate matter, such as diesel particulates and metallic fragments from subway wheels. *Micrococcus* species often dominate in urban air, perhaps associated with such particles (87, 110). The crucial point in the current context is that people living close to agricultural land have more biodiverse microbial populations on their skin than those living close to urban centers (47), and this correlates with immunoregulatory differences and reduced atopy. These organisms are also encountered via the airways and gut. By contrast, the use of biocides in the home may decrease microbial biodiversity (111).

Detrimental Microbiota in Unhealthy Buildings

This point leads on to a further problem with the environment in modern buildings. Humans evolved in a natural environment and

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in contact with animals. Until recently even our homes were constructed with timber, mud, animal hair, animal dung, thatch, and other natural products and were ventilated by outside air. By contrast, modern buildings are constructed with synthetic materials, plastics, and concrete, and the timber and cardboard are treated with adhesives and biocides, and the buildings are ventilated by air conditioning systems. When these modern structures degrade, become damp, or accumulate condensation in cavity walls, they do not become colonized with the bacterial strains with which we coevolved. They become habitats for unusual strains that we did not encounter during our evolutionary history, some of which synthesize toxic molecules that we are unable to inactivate (112, 113). Some examples of "sick building syndrome" have been tentatively attributed to prolonged exposure to these inappropriate airborne microbiota (112, 113).

Environment and the Human Microbiota

To what extent does exposure to these various environmental sources of microbial diversity directly modulate the human microbiota? Do organisms from green space become members of the human microbiota, or are these organisms "pseudocommensals" that impinge on the skin, airways, and gut and have independent immunoregulatory properties? Both mechanisms probably occur, although there are rather limited data on these issues. The environment does play an important role in the formation and maintenance of our microbiota. Fig. 3 illustrates several potential mechanisms.

From birth, our microbiota are constituted by colonization with organisms from our mothers, from other social contacts (107, 108), and from the environment, and then further modified by factors such as diet and antibiotics (114, 115). Thus, the lifestyle of the individual has major effects on that individual's microbiota. The gut microbiota of children from traditional villages in Burkina Faso is totally different from that of Europeans (114). An interesting animal experiment compared piglets that were housed in a natural outdoor environment with genetically similar piglets that had been reared in a very clean indoor facility. Firmicutes, in particular *Lactobacillus* strains, were dominant in the gut microbiotas of the outdoor piglets, whereas the hygienic indoor piglets had reduced *Lactobacillus* and more potentially pathogenic phylotypes (116). The indoor piglets also had dramatically different patterns of gene expression in the ileum, discussed in the next section (116). Were these effects due to direct colonization by immunoregulation-inducing organisms from the outdoor environment (pathway A in Fig. 3), or did these organisms fail to colonize but exerted indirect effects on the immune system? The answer is unclear, but indirect effects certainly can occur in several ways. Some organisms compete with or antagonize established organisms (pathway B) and therefore alter the microbiota (117). Others alter the immune system directly (pathway D) or modulate the immune system in ways that lead secondarily to a change in the host–microbiota relationship, which in turn leads to changes in the microbiota (pathway C in Fig. 3). The last mechanism is well established in experimental models. Genetic manipulations of the innate immune system that have profound effects on immune function (such as gene knockout) often operate indirectly by altering the gut microbiota. The phenotypic effects can then be transferred to WT mice that have not been genetically modified, by transferring the altered microbiota (118, 119). It is the altered microbiota that is the proximate cause of the altered immunoregulation (118, 119). At least one environmental saprophyte that will not colonize (and is dead when used in experimental models and in human clinical trials), can be shown to evoke immunoregulatory effects that suppress allergic responses whether injected s.c. (120) or given orally (121) and also exerts antidepressant-like effects on the CNS (122). Probiotic strains such as some lactobacilli can at least temporarily colonize the gut and induce changes in the microbiota via a variety of mechanisms discussed elsewhere (117).

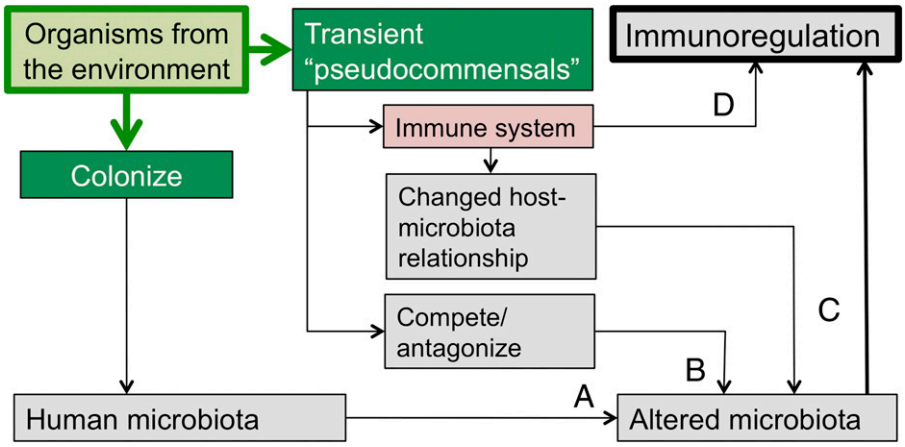


Fig. 3. Multiple ways in which the microbiota of the natural environment can modulate the immune system. This modulation may or may not involve colonization. There can be direct interaction with the immune system (pathway D) or indirect effects secondary to changes in the microbiota (pathways A, B, and C, fully explained in text).

Microbiota Diversity and Regulation of Inflammation

The piglets discussed in the previous section, which had been reared in clean interiors without exposure to the natural environment, had different patterns of gene expression in the ileum, much of it related to the immune system. For example, they had increased type 1 IFN activity, increased MHC class 1, and up-regulation of many chemokines (116), implying a more inflammatory state in the guts of animals whose microbiota had not been modified and diversified by exposure to the natural environment. This correlation between reduced gut microbial biodiversity and poor control of inflammation is a common finding. Mice exhibit at least two enterotypes (bacterial ecosystems in the gut microbiota), one of which has low biodiversity and correlates with biomarkers of inflammation (123). Gut microbiota of limited diversity is also characteristic of human inflammation-associated conditions such as obesity and inflammatory bowel disease (124, 125). Similarly, diminished microbiota biodiversity in institutionalized elderly people correlates with diminished health and raised levels of peripheral inflammatory markers such as IL-6 (109). Adequate microbial inputs are required to maintain diversity of the gut microbiota, and such diversity plays a role in the regulation of inflammation.

Microbial Biodiversity as an Ecosystem Service

Interestingly, provision of microbial biodiversity is not conventionally listed as an "ecosystem service." Ecosystem services are ecologically mediated functions essential to sustaining healthy human societies. Major reviews of these services do not contain the words inflammation or immunity (126, 127), despite the fact that the immunoregulatory roles of microorganisms have been known for decades. It is hoped that this perspective article will help to bridge the chasm between ecology and medicine/immunology, so that when ecologists consider how to maximize the services obtained from

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ecosystems, the contained microbial biodiversity is taken into consideration.

Psychology vs. Immunology

The major conclusion of this review is that the beneficial effects of exposure to natural environments are likely to have two separate but interacting components. First, there are well-established rapid psychological effects that might be explained by an evolved psychological reward from contemplating the ideal hunter-gatherer habitat. However, the specificity of the effect for green space has not been proven by comparison with other relaxing environments, and the relevance of such rapid transient changes for long-term health benefits is unknown.

However, there is good evidence that the long-term benefit of exposure to the natural environment is one component of a broad range of effects that fall under the umbrella terms hygiene hypothesis or Old Friends mechanism or biodiversity hypothesis. These terms refer to the evolved need for the immune system to receive inputs provided by microbial biodiversity, and in particular, by organisms that need to be tolerated, and therefore have coevolved roles as inducers of the immunoregulatory pathways (26, 27). These immunoregulatory mechanisms help to stop chronic inflammation and its associated chronic inflammatory diseases, cardiovascular problems, and depression (27). Unlike the rapid psychological effects, this requires prolonged exposures, particularly important during childhood when much of the education of the immune system occurs. It might not be sufficient to encounter only the biased microbiota of the modern synthetic indoor environment that lacks the Old Friends and probably bears little resemblance to the microbiota we encountered throughout our evolutionary history. As illustrated in Fig. 2, modern life deprives us of many of the inputs that our immune systems evolved to anticipate, so we are now more dependent on the microbiota of other people and the microbiota of the natural environment and green spaces. Fig. 4 provides a list of probable components of the beneficial effects of the natural environment, with the parallel psychological and immunological explanations. It seems likely that both types of explanation are important. The underlying principle of the immunological explanation is that for many reasons, exposure to green spaces will lead to increased immunoregulation, resulting in lower background inflammation, manifested as lower resting CRP. Improved control of inflammation results in lower prevalence of inflammatory disorders, cardiovascular disease, and depression and increased stress resilience (27). It is interesting that sunlight and exercise both contribute to this effect.

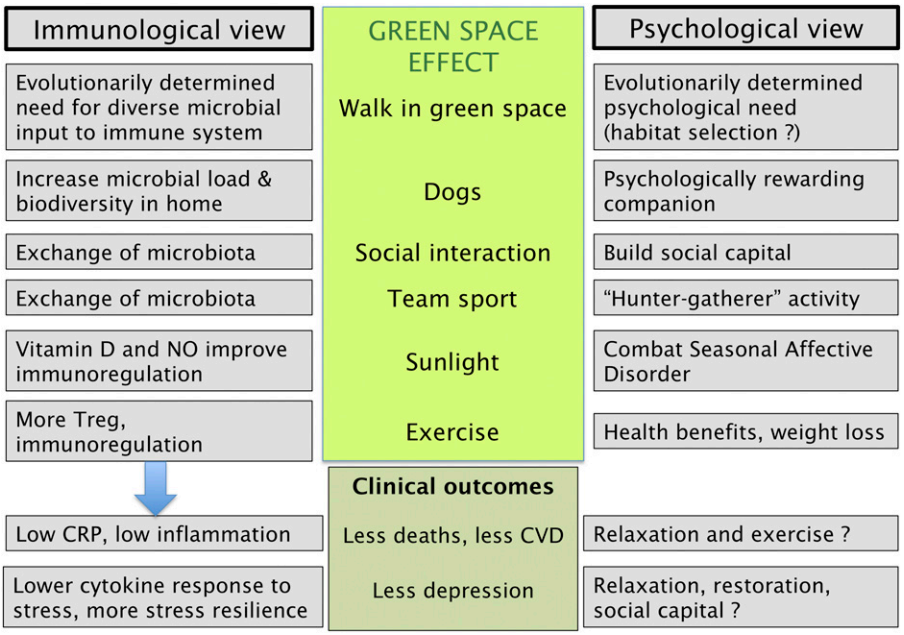


Fig. 4. Immunological and psychological explanations for the health benefits derived from contact with the natural environment. (NO, nitric oxide). There are many studies of exposures during the perinatal period that point to the immunological mechanisms, whereas most studies in adult life have been orientated toward psychological explanations, and have not included investigation of the immunoregulatory aspects.

Sunlight enhances production of vitamin D (128) and nitric oxide (129), both of which play critical roles in immunoregulation. Similarly exercise increases the activity of Tregs (21, 130). Therefore, multiple physiological consequences of exposure to the natural environment will supplement the immunoregulatory effects of microbial biodiversity.

Urgent Questions and Research Issues

Much research will be needed to consolidate this immuno-microbiological view of the health benefits of exposure to the natural environment. We need new epidemiological studies that concentrate on inflammatory disorders attributable to defective immunoregulation. More studies that use high sensitivity CRP levels as a surrogate biomarker for background inflammation will be valuable. We need more information about the organisms people encounter in their own homes and how this is affected by the proximity to natural environments and by the nature of that environment. Humans evolved as a grassland species, so we can guess, for example, that deserts and some types of monoculture might be less beneficial than grassland and its associated animals. The exposures of individuals can be monitored by sampling skin and gut microbiota and perhaps by studying antibodies. We have worryingly little knowledge about the relationship between environmental strains and those that colonize humans, because current methods of studying microbiota usually give only a broad taxonomic grouping.

If it turns out that the immuno-microbiological view is correct, we will also need to know when the educational and immunoregulatory inputs to our immune systems need to occur. At least some of the immunoregulatory effects of Old Friends are exerted very early in life. For example, factors that delay (caesarian births) or distort (perinatal antibiotic use) the establishment of the gut microbiota of the infant increase the frequency of allergic disorders (131, 132). Similarly, the reduced prevalence of allergic disorders after exposure to the farm environment only occurs if the exposure is during pregnancy or the neonatal period (79, 133). Does this mean that all these immunoregulatory effects occur during the perinatal period? Might it be sufficient to design preschool daycare centers so that infants are exposed to relevant microbiota? This view is unlikely because later childhood might also be important. For example, environmental factors, probably microbial, that influence the risk of developing MS in later life seem to operate during childhood up to the age of 10–15 y (65, 68, 69, 134). Therefore, could the problem be solved by ensuring the presence of appropriate organisms in homes and schools until after adolescence? This possibility also seems unlikely because we know that helminth infections, even when they did not enter the gut, were powerfully immunoregulatory even in adults (36–38), and there is mounting evidence that dysbiosis or diminished biodiversity of the gut microbiota is associated with a variety of inflammatory

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conditions (109, 124, 125). There is a worrying lack of data on this point, but overall, it seems probable that most education of the immune system occurs in the perinatal period but that there is also an ongoing requirement for microbial inputs throughout life.

Conclusions

It is interesting that the beneficial effects of proximity to the natural environment are particularly prominent in individuals of low socioeconomic status (1–3, 8). Perhaps wealthier individuals are better able to supplement such exposures with holiday travel and rural second homes. This disturbing health gradient emphasizes the need for more research that will enable us to design urban green spaces that provide not only the psychological input to our brains but also an optimized microbial input to our immune systems. The research outlined above will help us to know what is needed and when. If a significant part of the role of the natural environment is to provide an appropriate airborne microbiota, then multiple, small, widely distributed urban green spaces of high microbial quality might suffice as supplements to a core of large recreational parks. There is already huge interest in the construction of roof gardens, vertical gardens and urban green spaces motivated by aesthetics and by organizations wishing to promote urban habitats for birds and insects and by urban planners wishing to delay the entry of rain downpours in sewer systems. However, we suggest that combating the epidemic of inflammation-associated illnesses in high-income urban environments provides another compelling motive for creating green spaces, and we hope that this paper will enhance collaboration between the medical profession, ecologists, and urban planners.

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Lime Down Solar – Overview of Research Papers on Health Impacts as requested by the Planning Inspectorate 300626

OVERVIEW

'Good Nature' is a recently published book (2024) that I highly recommend reading as an excellent resource and summary of many of the papers that are referenced below and whose content is 100% relevant when considering the longterm potential health implications of Lime Down Solar.
It is authored by Kathy Willis, Professor of Biodiversity, University of Oxford; cross bench peer in the House of Lords; and ex Director of Science at the Royal Botanic Gardens, Kew.

NOTE
The papers cited below are a small selection of the hundreds of research articles and clinical data that I have read over the last 20 years that draw well founded scientific / medical / health conclusions regarding the myriad positive impacts of nature on the wellbeing, vitality and healing journey of the clients / patients with whom we come in to contact on a daily basis.

Due to the proposed 60 year plus lifespan of Lime Down Solar, I have focussed on the detrimental effects such a scheme would have on the 20,000 children's lives that would be adversely affected by such a huge project, inappropriately sited on 2,220 acres of beautiful green space and farmland surrounding the rural communities of North Wiltshire.

KEY
Index = Papers attached as pdf (where available to the public)
Year = Year of Publication

Abstracts of each paper by the author(s) are noted in the accompanying document 'Lime Down Solar - Research Papers & Abstracts'

Index	Paper	Author(s)	Journal	Year	Link
GENERAL OVERVIEW PAPERS In the Lime Down Solar planning application there are limited details of how Lime Down Solar are demonstrating that people will continue to have access to adequate greenspace within the 2,220 acres of solar panels. There is a general commitment to biodiversity net gain and connectivity, yet the various impacts of health, vitality, wellbeing and specifically cognitive development and mental health are barely touched upon.					
001 Details of Paper	**Annual Review of Public Health**	[redacted]	**Nature and Health**	**2014**	35(1), 207–228 www.annualreviews.org/content/journals/10.1146/annurev-publhealth-032013-182443
002 Details of	**Growing up green:**		**Nature Journal of Exposure**	**2022**	[redacted]

Paper	**A systematic review of the influence of greenspace on youth development and health outcomes**		**Science & Environmental Epidemiology**		
003 Details of Paper	**Greenspace and health, wellbeing, physical activity, and development in children and adolescents:** **An overview of the systematic reviews**	[redacted]	**Science**	**2023**	[redacted]
004 Details of Paper	**Nature and Children's Health:** **A Systematic Review**		**PubMed**	**2021**	https://pubmed.ncbi.nlm.nih.gov/34588297/
005 Details of Paper	**Effects of Nature (Greenspace) on Cognitive Functioning in School Children and Adolescents: A Systematic Review**		**Nature Educational Psychology Review**	**2022**	[redacted]
THE IMPACT OF GREENNESS AND TREES ON HEALTH What consideration have Lime Down Solar given during the pre construction phase to replacing the volume and, critically, the maturity of trees and hedgerows that will be decimated by the large area to be covered in solar panels. Where is the written evidence to show that Lime Down Solar have systematically reviewed the scale of the implications of their planning application on both the short term and long term health and wellbeing of the surrounding population, specifically on mental health, cognitive ability and levels of stress in relation to the light industrialisation / urbanisation vs current farmland, rolling countryside vistas & abundance of green landscapes of North Wiltshire.					
006 Details of Paper	**Residential greenness and prevalence of major depressive disorders: a cross- sectional, observational, associational study of 94,879 adult UK BioBank participants**	[redacted]	**The Lancet Planetary Health**	**2018**	2, e162 – e173 [redacted]
007	**Impact of Views to school**		**Landscape and Urban**	**2016**	148, pp149-58

Details of Paper	**landscapes on recovery from stress and mental fatigue**	[redacted]	**Planning**		[redacted]
008 Details of Paper	**Green spaces and cognitive development in primary schoolchildren**		**Proceedings of the National Academy of Sciences**	**2015**	112, pp 7,937 – 7,942 www.pnas.org/doi/10.1073/pnas.1503402112
009 Details of Paper	**The restorative benefits of nature: Toward an integrative framework**		**Journal of Environmental Psychology**	**1995**	15, pp 169 – 82 [redacted]
010 Details of Paper	**Why viewing nature is more fascinating and restorative than viewing buildings:** **A closer look at perceived complexity**		**Urban Forestry & Urban Greening**	**2016**	20, pp 397 – 401 [redacted]
TO THRIVE, THE HUMAN BODY NEEDS GREENNESS & COLOURS / SMELLS OF NATURE Lime Down Solar would cover 2,220 acres with inert grey black reflective structures of large solar panels releasing toxic VOCs in to the atmosphere vs health enhancing VOCs from conifers and trees. What mitigation factors have been considered to remove dense clouds of toxins from the air, particularly as the solar panels degrade. How much greenness of nature will be visible vs black/grey of mechanical and metallic structures across the Lime Down Solar site. Fencing should be green and brown, and made of wooden or other natural materials, that have proven beneficial calming effects. How will the depletion of beneficial terpenes be mitigated so the site will not have detrimental affects on the body's natural killer (NK) cells, resulting in weakened immune systems and chronic health issues.					
011 Details of Paper	**Visual colour perception in green exercise: Positive effects on mood and perceived exertion**	[redacted]	**Environmental Science & Technology**	**2012**	46, pp 8,661 -8,666 [redacted]
012	**The processing of colour**	[redacted]	**Neuroimage**	**2019**	191, pp 529-536

Details of Paper	**preference in the brain**	[redacted]			[redacted]
013 Details of Paper	**Conifer derived monoterpenes and forest walking**		**Mass Spectrometry**	**2015**	4, A0042 [redacted]
014 Details of Paper	**Health effects of a forest environment on natural killer cells in humans:** **An observational pilot study**		**Oncotarget**	**2018**	9, 16,501 [redacted]

THE IMPACT OF SOUNDS OF NATURE vs MECHANICAL NOISE ON HEALTH

There is a large body of evidence regarding the strong negative impact of certain mechanical and electrical sounds on health vs. natural sounds that help in alleviating stress, restoring vitality and relieving pain.

In the construction phase how are Lime Down Solar going to ensure that reasonable hours of work operation are being enforced without juggernauts rumbling down narrow country lanes, lorries beeping on site when reversing, etc and village homes selected for peace and quiet disturbed daily for 3 years, followed by not insignificant background noise levels in the long term.

Have sonic protection, critical re-housing and respite provisions been included in the plans to allow our most vulnerable children and those with serious health problems to have adequate sleep and quiet study / recovery time.

Has adequate consideration been given to the ornithological impact of the lack of hedgerows and the consequent requirement for significant additional planting to encourage the return of bird species to the area after the construction phase, and thus mitigate the initial negative effect on the current restorative human environment across the nine villages that would be effected.

015 Details of Paper	**Restorative qualities of and preference for natural or urban soundscapes**	[redacted]	**Frontiers in psychology**	**2017**	8, 1705 https://pmc.ncbi.nlm.nih.gov/articles/PMC5632731/
016 Details of Paper	**Predicting the restorative potential of bird sounds through acoustics and aesthetics**	[redacted]	**Environment & Behaviour**	**2020**	52, pp 371-400 [redacted]

		[redacted]			ustics_and_Aesthetics
017 Details of Paper	**Associations with bird sounds: How do they relate to perceived restorative potential ?**		**Journal of Environmental Psychology**	**2016**	47, pp 136 – 144 https://doi.org/10.1016/j.jenvp.2016.5.009 [redacted]
018 Details of Paper	**Of cricket chirps and car horns: The effect of nature sounds on cognitive performance**		**Psychonomic Bulletin & Review**	**2019**	26, pp522 – 530, https://doi.org/10.3758/s13423-018-1539-1
019 Details of Paper	**A synthesis of health benefits of natural sounds and their distribution in national parks**		**Proceedings of the National Academy of Sciences**	**2021**	118, e2013097118
020 Details of Paper	**Urban greenspace soundscapes and their perceived restorativeness**		**People and Nature**	**2021**	3, pp756 – 769 [redacted]

THE BENEFITS OF HORTICULTURE & TOUCHING NATURE

Horticultural therapy is a well recognised occupational health intervention for both physical wellbeing and mental health conditions, depression, ADHD, autism and, in addition, memory loss in older people. Touching live plants is proven to have a calming effect on the central nervous system. Walking barefoot in nature induces physiological calming and psychological relaxation compared with marble, concrete etc.

Should the current planning application be successful, it would result in the loss of a large swathe of countryside to solar panels and BESS units, and the erection of high fencing throughout the thousands of acres of the site.

What factors have been considered and what provisions made by Lime Down Solar for children to continue to benefit from free access to their local countryside, which is known to help minimise mental stress and significantly promote wellbeing vs staying indoors and using smartphones, and enables them to participate in horticultural and associated nature based activities that improve brain activity, help concentration and promote psychological relaxation.

021 Details of Paper	**Assessment of the psychpathological effects of a horticultural therapy programme in patients with schizophrenia**	[redacted]	**Complementary Therapies in Medicine**	**2018**	36, pp 54-8 [redacted]

022 Details of Paper	**Psychological & Physiological effect in humans of touching plant foliage – cerebral activity as indicators**	[redacted]	**Journal of Physiological Anthropology**	**2013**	32, pp 1-9 [redacted]
023 Details of Paper	**Physiological effects of touching the wood of hinoki cypress trees with the soles of the feet**		**International Journal of environmental Research and Public Health**	**2018**	15, 2135 [redacted]
024 Details of Paper	**Horticultural activity: Its contribution to stress recovery and wellbeing for children**		**International Journal of environmental Research and Public Health**	**2020**	17, 1229 [redacted]
025 Details of Paper	**Comparing concentration levels and emotional states of children using electroencephalography during horticultural and non-horticultural activities**		**Hort Science**	**2021**	56, pp 324-9 [redacted]

EXPOSURE TO THE ENVIRONMENTAL MICROBIOME

Exposure to microbes associated with plants, soil and the air around them has a profound impact on gut health. Less than 8 per cent of our gut composition is now thought to be due to genetic inheritance; the rest is due to our lifestyle and the environment.

A strong biological link to nature and the requirement for microbial input from the environment to drive immuno-regulation is a major component of the beneficial effect of green space. Children playing outside leads to increased levels of cytokines and T cells which help prevent autoimmune conditions, IBS, coeliac disease and increases the diversity of microbiota on the skin and in the gut.

During the potential 60 year lifespan, how do Lime Down Solar propose to manage and ameliorate biodiversity across the ancient pastures of North Wiltshire so as not to be responsible for a neglected and unbalanced ecosystem throughout the 2,220 acre greenspace.

Declining biodiversity can increase the risk to humanity from chronic diseases and thereby cause a major public health problem. Without well considered advanced planning, the disruption to the current diverse natural environment caused by the long term development of the Lime Down Solar site, may result in a lack of regular exposure to the wide range of microbes that are essential for our well-being, and help maintain or restore a healthy gut microbiome.

026 Details of	**Biodiversity intervention enhances immune regulation and health**	[redacted]	**Science Advances**	**2020**	6, eaba2578 [redacted]/

Paper	**associated commensal microbiota among daycare children**				[redacted]
027 Details of Paper	**What is the healthy gut microbiota composition? A changing ecosystem across age, environment, diet, and diseases & The gut microbiome in hypertension: recent advances and future perspectives**	[redacted]	**Circulation Research**	**2021**	128, pp 934-50 [redacted]
028 Details of Paper	**The human microbiome**		**Advances in Medical Sciences**	**2017**	62, 99 414-20 [redacted]
029 Details of Paper	**Natural Immunity: biodiversity loss and inflammatory diseases are two global megatrends that might be related**		**EMBO Reports**	**2011**	12, 1,089-93 [redacted]
030 Details of Paper	**Regulation of the immune system by biodiversity from the natural environment: an ecosystem service essential to health**		**Proceedings of the National Academy of Sciences**	**2013**	110, pp 18,260-7 www.pnas.org/doi/10.1073/pnas.1313731110

The book ‘Good Nature’ by [redacted]s and the selection of papers cited above (and attached) are some of the more relevant scientific papers regarding the impact of nature and the access to greenspace on children's development, cognitive, mental and physical, that should be understood and thoroughly reviewed in advance of the Lime Down Solar project being further considered.

CONFIDENTIAL
FORMATTING NOTE

The narrow final column has book references to [redacted] publication ‘Good Nature’
The text of these is in WHITE so is not visible in the Final PDF

Lime Down Solar - Research Papers on Health Impacts as requested by the Planning Inspectorate 300626

RESEARCH PAPERS and ABSTRACTS

To be read in conjunction with accompanying document 'Overview of Research Papers on Health Impacts for the Planning inspectorate'.

NOTE
The papers cited below are a small selection of the hundreds of research articles and clinical data that I have read over the last 20 years that draw well founded scientific / medical / health conclusions regarding the myriad positive impacts of nature on the wellbeing, vitality and healing journey of the clients / patients with whom we come in to contact on a daily basis.

Due to the proposed 60 year plus lifespan of Lime Down Solar, I have focussed on the detrimental effects such a scheme would have on the 20,000 children's lives that would be adversely affected by such a huge project, inappropriately sited on 2,220 acres of beautiful green space and farmland surrounding the rural communities of North Wiltshire.

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001	**Annual Review of Public Health**	[redacted]	**Nature and Health**	**2014**
Abstract	Urbanization, resource exploitation, and lifestyle changes have diminished possibilities for human contact with nature in many societies. Concern about the loss has helped motivate research on the health benefits of contact with nature. Reviewing that research here, we focus on nature as represented by aspects of the physical environment relevant to planning, design, and policy measures that serve broad segments of urbanized societies. We discuss difficulties in defining "nature" and reasons for the current expansion of the research field, and we assess available reviews. We then consider research on pathways between nature and health involving air quality, physical activity, social cohesion, and stress			

	reduction. Finally, we discuss methodological issues and priorities for future research. The extant research does describe an array of benefits of contact with nature, and evidence regarding some benefits is strong.			
002	**Growing up green:** **A systematic review of the influence of greenspace on youth development and health outcomes**	[redacted]	**Nature** **Journal of Exposure Science & Environmental Epidemiology**	**2022**
Abstract	Youth growing up in places with more greenspaces have better developmental outcomes. The literature on greenspace and youth development is largely cross-sectional, thus limited in terms of measuring development and establishing causal inference. We conducted a systematic review of prospective, longitudinal studies measuring the association between greenspace exposure and youth development outcomes measured between ages two and eighteen. Study quality was assessed using a 10-item checklist adapted from a previously published review on greenspace and health. Twenty-eight studies met criteria for review and were grouped into five thematic categories based on reported outcomes: - cognitive and brain development, - mental health and wellbeing, - attention and behaviour, - allergy and respiratory, and - obesity and weight. 79% of studies suggest an association between greenspace and improved youth development.			
003	**Greenspace and health, wellbeing, physical activity, and development in children and adolescents:** **An overview of the systematic reviews**	[redacted]	**Science**	**2023**
Abstract	The evidence on the beneficial association of greenspace exposure and mental and physical health and wellbeing of children and adolescents is accumulating.			

	We systematically searched PubMed, Scopus, and Web of Science for systematic reviews and/or meta-analyses on health, developmental, and behavioural outcomes in children and adolescents related to greenspace exposure, published until August 2022. Most of the available reviews are on mental health and behavioural outcomes. Overall, reviews are suggestive of a beneficial association of greenspace with a range of outcomes *e.g.*, birth, neurodevelopmental, cognitive, behavioural, weight-related, mental health and wellbeing, school performance, and physical and outdoor activities), except for allergic and respiratory outcomes for which the evidence is not conclusive.			
004	**Nature and Children's Health:** **A Systematic Review**	[redacted]	**PubMed**	**2021**
Abstract	Current literature supports a positive relationship between nature contact and children's health, especially for physical activity and mental health, both public health priorities. The evidence supports paediatricians in advocating for equitable nature contact for children in places where they live, play, and learn.			
005	**Effects of Nature (Greenspace) on Cognitive Functioning in School Children and Adolescents: A Systematic Review**	[redacted]	**Nature Educational Psychology Review**	**2022**
Abstract	There is growing interest in understanding the extent to which natural environments can influence learning particularly in school contexts. Nature has the potential to relieve cognitive overload, reduce stress and increase wellbeing - all factors that are conducive to learning. This paper provides a PRISMA-guided systematic review of the literature examining the effects of nature interventions on the cognitive functioning of young people aged 5 to 18 years. Examples of nature interventions include outdoor learning, green playgrounds, walks in nature, plants in classrooms and nature views from classroom windows. These can vary in duration and level of interaction (passive or active). Results provide substantial support for cognitive benefits of nature interventions regarding selective attention, sustained attention and working memory. Underlying mechanisms for the benefits were also explored, including enhanced wellbeing, cognitive restoration and stress reduction - all likely to be contributors to the nature-cognition relationship. <u>Introduction</u>: The pressure of modern-day westernized living involving technology, high-rise buildings, traffic congestion and pollution is taking a toll on society.			

These lifestyle changes have led to reduced opportunities for interacting with nature (Hartig et al., 2014) and a fast-paced lifestyle that can be psychologically draining.

Subsequently health and well-being are compromised as evidenced by escalating rates of mental illness (Blake et al., 2018; Michaelson et al., 2020; Vancampfort et al., 2018).

In an attempt to reduce fatigue and improve well-being, research attention has turned to the potential healing effects of nature (Capaldi et al, 2015; Diaz et al., 2015; Hartig et al. 2014).

THE IMPACT OF GREENNESS AND TREES ON HEALTH

What consideration have Lime Down Solar given during the pre construction phase to replacing the volume and, critically, the maturity of trees and hedgerows that will be decimated by the large area to be covered in solar panels.

Where is the written evidence to show that Lime Down Solar have systematically reviewed the scale of the implications of their planning application on both the short term and long term health and wellbeing of the surrounding population, specifically on mental health, cognitive ability and levels of stress in relation to the light industrialisation / urbanisation vs current farmland, rolling countryside vistas & abundance of green landscapes of North Wiltshire.

006	**Residential greenness and prevalence of major depressive disorders: a cross- sectional, observational, associational study of 94,879 adult UK BioBank participants**	[redacted]	**The Lancet Planetary Health**	**2018**
Abstract	Increased urbanisation and the associated reduced contact of individuals with natural environments have led to a rise in mental disorders, including depression. Residential greenness, a fundamental component of urban design, has been shown to reduce the public health burden of mental disorders. The present study investigates the association between residential green exposure and prevalence of major depressive disorders using a large and diverse cross-sectional dataset from the UK Biobank.			

007	**Impact of Views to school landscapes on recovery from stress and mental fatigue**	[redacted]	**Landscape and Urban Planning**	**2016**
Abstract	Previous research has demonstrated positive associations between the greenness of high school landscapes and school wide academic performance.			

	We hypothesize that views onto green landscapes help students recover from mental fatigue and stress. Participants were randomly assigned to classrooms without windows or with windows that opened onto a built space or a green space. Participants engaged in typical classroom activities followed by a break in the classroom to which they were assigned. Results demonstrate that classroom views to green landscapes cause significantly better performance on tests of attention and increase student's recovery from stressful experiences. A lack of mediation effect demonstrates that attention restoration and stress recovery are two distinct processes. Implications for school site selection, design and renovation are discussed.			
008	**Green spaces and cognitive development in primary schoolchildren**	[redacted]	**Proceedings of the National Academy of Sciences**	**2015**
Abstract	Green spaces have a range of health benefits, but little is known in relation to cognitive development in children. This study, based on comprehensive characterization of outdoor surrounding greenness (at home, school, and during commuting) and repeated computerized cognitive tests in schoolchildren, found an improvement in cognitive development associated with surrounding greenness, particularly with greenness at schools. This association was partly mediated by reductions in air pollution. Our findings provide policymakers with evidence for feasible and achievable targeted interventions such as improving green spaces at schools to attain improvements in mental capital at population level.			
009	**The restorative benefits of nature: Toward an integrative framework**	[redacted]	**Journal of Environmental Psychology**	**1995**
Abstract	Directed attention plays an important role in human information processing; its fatigue, in turn, has far-reaching consequences. Attention Restoration Theory provides an analysis of the kinds of experiences that lead to recovery from such fatigue. Natural environments turn out to be particularly rich in the characteristics necessary for restorative experiences. An integrative framework is proposed that places both directed attention and stress in the larger context of human-environment relationships.			
010	**Why viewing nature is more fascinating and restorative than viewing buildings:** **A closer look at perceived complexity**	[redacted]	**Urban Forestry & Urban Greening**	**2016**

Abstract	The present paper addresses the question which visual features trigger people's often more positive affective responses to natural compared to built scenes. Building on notions about visual complexity and fractal geometry, we propose that perceived complexity of magnified scene parts can predict the greater fascinating and restorative qualities of natural versus built scenes. This prediction was tested in an experiment in which 40 participants viewed and rated 40 images of unspectacular natural and built scenes in their original size, and at 400% and 1600% magnification levels. Results showed that the original, unmagnified natural scenes were viewed longer and rated more restorative than built scenes, and that these differences were statistically mediated by the greater perceived complexity of magnified parts of natural scenes. These findings fit with the idea that fractal-like, recursive complexity is an important visual cue underlying the restorative potential of natural and built environments.

TO THRIVE, THE HUMAN BODY NEEDS GREENNESS & COLOURS / SMELLS OF NATURE

Lime Down Solar would cover 2,220 acres with inert grey black reflective structures of large solar panels releasing toxic VOCs in to the atmosphere vs health enhancing VOCs from conifers and trees. What mitigation factors have been considered to remove dense clouds of toxins from the air, particularly as the solar panels degrade.

How much greenness of nature will be visible vs black/grey of mechanical and metallic structures across the Lime Down Solar site. Fencing should be green and brown, and made of wooden or other natural materials, that have proven beneficial calming effects.

How will the depletion of beneficial terpenes be mitigated so the site will not have detrimental affects on the body's natural killer (NK) cells, resulting in weakened immune systems and chronic health issues.

011	**Visual colour perception in green exercise: Positive effects on mood and perceived exertion**	[redacted]	**Environmental Science & Technology**	**2012**

Abstract	A significant interaction between test time and colour perception indicated that anger decreased in the two green colour conditions. A significant interaction of colour perception by form perception by test time was associated with a significant decrease in response times on the attention task after cycling among participants who viewed the green tree. Our findings are important for interpreting mechanisms underlying characteristics attributable to environmental benefits and revealed that single (colour or form) or combined (colour and form) visual perception improved the mental health benefits of exercise.

	These findings may also inform the design and planning of urban green spaces to maximize green exercise effects.			
012	**The processing of colour preference in the brain**	[redacted]	**Neuroimage**	**2019**
Abstract	We looked for correlations of a behavioural measure of colour preference with the blood oxygen level-dependent (BOLD) response when participants performed an irrelevant orientation judgement task on coloured squares. A whole brain analysis found a significant correlation between BOLD activity and colour preference in the posterior midline cortex (PMC), centred on the precuneus but extending into the adjacent posterior cingulate and cuneus. These results demonstrate that brain activity is modulated by colour preference, even when such preferences are irrelevant to the ongoing task the participants are engaged. They also suggest that colour preferences automatically influence our processing of the visual world. Interestingly, the effect in the PMC overlaps with regions identified in neuroimaging studies of preference and value judgements of other types of stimuli. Therefore, our findings extends this literature to show that the PMC is related to automatic encoding of subjective value even for basic visual features such as colour.			
013	**Conifer derived monoterpenes and forest walking**	[redacted]	**Mass Spectrometry**	**2015**
Abstract	Conifer and broadleaf trees emit volatile organic compounds in the summer. The major components of these emissions are volatile monoterpenes. Using solid phase micro extraction fibre as the adsorbent, monoterpenes were successfully detected and identified in forest air samples. Gas chromatography / mass chromatogram of monoterpenes in the atmosphere of a conifer forest and that of serum from subjects who were walking in a forest were found to be similar each other. The amounts of α-pinene in the subjects became several folds higher after forest walking. The results indicate that monoterpenes in the atmosphere of conifer forests are transferred to and accumulate in subjects by inhalation while they are exposed to this type of environment.			
014	**Health effects of a forest environment on natural killer cells in humans:**	[redacted]	**Oncotarget**	**2018**

	An observational pilot study			
Abstract	Health effect assessments based on natural killer (NK) cells are an important emerging area of human health. We recruited 90 forest staff members in Xitou, Taiwan and 110 urban staff members in Taipei to investigate the health effects of forest environment exposure on NK cells (CD3−/CD56+) and activating NK cells (CD3−/CD56+/CD69+) in humans. We also invited 11 middle-aged volunteers in a pilot study to participate in a five-day/four-night forest trip to Xitou forest to investigate the health effects of a forest trip on NK cells and activating NK cells. Results showed that NK cells were higher in the forest group (19.5 ± 9.1%) than in the urban group (16.4 ± 8.4%). In particular, the percentage of NK cells was significantly higher in the forest group than in the urban group among the subgroups of male, a higher body mass index (≥ 25 kg/m2), without hypertension, lower high-sensitivity C-reactive protein, hyperglycaemia, without smoking habit, and with tea drinking habit. This study suggests that exposure to forest environments might enhance the immune response of NK cells and activating NK cells in humans.			

THE IMPACT OF SOUNDS OF NATURE vs MECHANICAL NOISE ON HEALTH

There is a large body of evidence regarding the strong negative impact of certain mechanical and electrical sounds on health vs. natural sounds that help in alleviating stress, restoring vitality and relieving pain.

In the construction phase how are Lime Down Solar going to ensure that reasonable hours of work operation are being enforced without juggernauts rumbling down narrow country lanes, lorries beeping on site when reversing, etc and village homes selected for peace and quiet disturbed daily for 3 years, followed by not insignificant background noise levels in the long term.

Have sonic protection, critical re-housing and respite provisions been included in the plans to allow our most vulnerable children and those with serious health problems to have adequate sleep and quiet study / recovery time.

Has adequate consideration been given to the ornithological impact of the lack of hedgerows and the consequent requirement for significant additional planting to encourage the return of bird species to the area after the construction phase, and thus mitigate the initial negative effect on the current restorative human environment across the nine villages that would be effected.

015	**Restorative qualities of and preference for natural or urban soundscapes**	[redacted]	**Frontiers in psychology**	**2017**

Abstract	Psychological restoration in urban agglomerations has become a growing challenge. Although scientific proof of the significance of nature is irrefutable, an increase in built-up areas has led to a decrease in urban greenery. Thus, a growing need for restorativeness in urban surroundings has emerged. To investigate whether positively evaluated sonic environments, represented by natural and urban sounds, have comparable restorative qualities we conducted two studies. The aim of the first (Study 1) was to explore the restorative qualities of positively assessed natural and urban sounds. Participants (*N* = 88) were asked to listen and to rate 22 recordings (each 1 min long) either from natural or urban environments. In the second (Study 2) we investigated whether positively evaluated sonic environments (natural and urban), demand for restoration (feeling relaxed or fatigued) and company (being alone or with a friend) affect the restorative qualities of natural and urban soundscapes… Our findings confirmed that natural sounds are perceived more favourably than urban recordings. Even when only the most positively assessed soundscapes were compared, nature was still perceived as being more restorative than urban areas.

016	**Predicting the restorative potential of bird sounds through acoustics and aesthetics**		**Environment & Behaviour**	**2020**

Abstract	Some, but not all, bird sounds are associated with perceptions of restoration from stress and cognitive fatigue. In this online study, ratings of perceived restorative potential (PRP) and aesthetic properties of 50 bird sounds were provided by 174 residents of the United Kingdom. Regression analyses demonstrated that sound level, harmonics, and frequency, and perceptions of complexity, familiarity, and pattern, were significant predictors of PRP and cognitive and affective appraisals of bird sounds. These findings shed light on the structural and perceptual properties that may influence restorative potential of acoustic natural stimuli. Finally, through their potential associations with meaning, these findings highlight the importance of further study of semantic or meaning-based properties within the restorative environments literature.

017	**Associations with bird sounds: How do they relate to perceived restorative potential ?**		**Journal of Environmental Psychology**	**2016**

Abstract	Bird sounds are related to perceptions of attention restoration and stress recovery, but the role of associations in such perceptions is

	understudied. Adult residents of the United Kingdom rated bird sounds on perceived restorative potential (PRP) and provided qualitative data on associations with each sound. Bird sounds were associated with imagined environments, birds and other animals, time and season, and activities within the environment. Bird sounds rated as high in PRP were associated with green spaces, spring and summer, daytime, and active behaviours in the environment. Low-PRP bird sounds were associated with exotic and marine environments, non-avian animals, and showed a non-significant trend towards associations with negative bird behaviour. These findings highlight connections between semantic values and restorative perceptions of natural stimuli. Such connections can inform top-down approaches to study of restorative environments and may benefit conservationists seeking to improve bonds between people and wildlife.

018	**Of cricket chirps and car horns: The effect of nature sounds on cognitive performance**	[redacted]	**Psychonomic Bulletin & Review**	**2019**

Abstract	Attention restoration theory (ART) posits that stimuli found in nature may restore directed attention functioning by reducing demands on the endogenous attention system. In the present experiment, we assessed whether nature-related cognitive benefits extended to auditory presentations of nature, a topic that has been understudied. To assess directed attention, we created a composite measure consisting of a backward digit span task and a dual n-back task. Participants completed these cognitive measures and an affective questionnaire before and after listening to and aesthetically judging either natural or urban soundscapes (between-participants). Relative to participants who were exposed to urban soundscapes, we observed significant improvements in cognitive performance for individuals exposed to nature. Urban soundscapes did not systematically affect performance either adversely or beneficially. Natural sounds did not differentially change positive or negative affect, despite these sounds being aesthetically preferred to urban sounds. These results provide initial evidence that brief experiences with natural sounds can improve directed attention functioning in a single experimental session.

019	**A synthesis of health benefits of natural sounds and their distribution in national parks**	[redacted]	**Proceedings of the National Academy of Sciences**	**2021**

Abstract

Parks are important places to listen to natural sounds and avoid human-related noise, an increasingly rare combination.

We first explore whether and to what degree natural sounds influence health outcomes using a systematic literature review and meta-analysis.

Examples of beneficial outcomes include decreased pain, lower stress, improved mood, and enhanced cognitive performance.

Given this evidence, and to facilitate incorporating public health in US national park soundscape management, we then examined the distribution of natural sounds in relation to anthropogenic sound at 221 sites across 68 parks.

National park soundscapes with little anthropogenic sound and abundant natural sounds occurred at 11.3% of the sites. Parks with high visitation and urban park sites had more anthropogenic sound, yet natural sounds associated with health benefits also were frequent.

These included animal sounds (audible for a mean of 59.3% of the time, SD: 23.8) and sounds from wind and water (mean: 19.2%, SD: 14.8).

Urban and other parks that are extensively visited offer important opportunities to experience natural sounds and are significant targets for soundscape conservation to bolster health for visitors.

Our results assert that natural sounds provide important ecosystem services, and parks can bolster public health by highlighting and conserving natural soundscapes.

020	**Urban greenspace soundscapes and their perceived restorativeness**	[redacted]	**People and Nature**	**2021**

Abstract

Past research has largely focused on visual stimuli, yet the auditory pathway is also an important means for contact with nature.

The sonic environments of urban green spaces, however, are rarely entirely natural and many differ in their composition of natural sounds and anthropogenic noise. Few studies have investigated how these differences may impact the restorative potential of these soundscapes and, in particular, how the presence of traffic noise may constrain the benefits of natural sounds.

To address this gap, we examined differences in the perceived restorativeness and perceived restorative outcomes across a gradient of eight park soundscapes that differed in bird and traffic sounds.

In a laboratory setting, 162 participants listened to sound samples and reported on perceptions of the soundscapes and restorative potential and outcomes.

The results strongly indicate that park soundscapes with a rich array of perceived bird sounds and minimal perceived traffic noise offer the greatest perceived restoration.

Traffic noise was found to moderate the positive effect of bird sounds. The duration of time lived in the city and noise sensitivity were also positively associated with greater perceived restorative benefits while noise□sensitive people were also more negatively affected by traffic noise.

The promotion of highly natural soundscapes in urban green spaces and the reduction of traffic noise can provide nature□based solutions to human health and well□being in urban areas.

THE BENEFITS OF HORTICULTURE & TOUCHING NATURE

Horticultural therapy is a well recognised occupational health intervention for both physical wellbeing and mental health conditions, depression, ADHD, autism and, in addition, memory loss in older people. Touching live plants is proven to have a calming effect on the central nervous system. Walking barefoot in nature induces physiological calming and psychological relaxation compared with marble, concrete etc.

Should the current planning application be successful, it would result in the loss of a large swathe of countryside to solar panels and BESS units, and the erection of high fencing throughout the thousands of acres of the site.

What factors have been considered and what provisions made by Lime Down Solar for children to continue to benefit from free access to their local countryside, which is known to help minimise mental stress and significantly promote wellbeing vs staying indoors and using smartphones, and enables them to participate in horticultural and associated nature based activities that improve brain activity, help concentration and promote psychological relaxation.

021	**Assessment of the psychpathological effects of a horticultural therapy programme in patients with schizophrenia**	**Y A Oh, S A Park & B E Ahn**	**Complementary Therapies in Medicine**	**2018**

Abstract

A horticultural therapy program improved the scores of schizophrenic patients in the Positive and Negative Syndrome Scale.
A horticultural therapy program improved clinical symptoms in the Brief Psychiatric Rating Scale of schizophrenic patients.
A horticultural therapy program significantly improved psychopathological symptoms of patients with schizophrenia.

This study showed the potential of horticultural therapy for improving psychopathologic symptoms of psychiatric patients.

022	**Psychological & Physiological effect in humans of touching plant foliage – cerebral activity as indicators**	**K Koga, & Y Iwasaki**	**Journal of Physiological Anthropology**	**2013**

Abstract

Numerous studies have reported on the healing powers of plants and nature, but there have not been so many instances of experimental research. In particular, there are very few psychological and physiological studies using tactile stimuli.

This study examines the psychological and physiological effects of touching plant foliage by using an evaluation profile of the subjects' impressions and investigating cerebral blood flow.

The fabric stimulus gave people 'soft' and 'rough' impressions, 'kind', 'peaceful' and 'pleasant' feelings psychologically, and a sense of physiological calm.

On the other hand, the metal stimulus gave people 'cold', 'smooth' and 'hard' impressions and an image of something 'artificial'. The metal stimulus caused a stress response in human cerebral blood flow although its evaluation in terms of 'pleasant or unpleasant' was neutral.

There were no remarkable differences between the stimuli of natural and artificial pothos compared with other types of stimulus psychologically. However, only the natural pothos stimulus showed a sense of physiological calm in the same appearance as the fabric stimulus.

This study shows that people experience an unconscious calming reaction to touching a plant. It is to be concluded that plants are an indispensable element of the human environment.

023	**Physiological effects of touching the wood of hinoki cypress trees with the soles of the feet**	**H Ikei, C Song & Y Miyazaki**	**International Journal of environmental Research and Public Health**	**2018**

Abstract

This study aimed to clarify the physiological effects of touching hinoki cypress (hereinafter called "hinoki") (*Chamaecyparis obtusa*) wood with the palm of the right hand on brain activity and autonomic nervous activity.

Twenty-two female university students (mean age 21.1 ± 0.2 years) participated in the study. As an indicator of brain activity, oxyhemoglobin (oxy-Hb) concentrations were measured in the left/right prefrontal cortex using near-infrared time-resolved spectroscopy.

Marble was used as a control material. After sitting at rest with their eyes closed, the participants touched the materials for 90s with their eyes still closed.

The results showed that tactile stimulation with hinoki wood significantly decreased oxy-Hb concentration in the left prefrontal cortex and

	increased ln(HF) reflected parasympathetic nervous activity compared with marble. In conclusion, our study showed that touching hinoki wood with the palm calms prefrontal cortex activity and increases parasympathetic nervous activity, thereby inducing physiological relaxation.			
024	**Horticultural activity: Its contribution to stress recovery and wellbeing for children**	**Y Shao, M Elsadek & B Liu**	**International Journal of Environmental Research and Public Health**	**2020**
Abstract	In recent years, children's use of mobile phones has grown rapidly, which might lead to an increase in mental stress and negatively affect their health. Despite increasing evidence that horticultural activity can provide significant health benefits, few scientific evidence-based studies are currently available regarding these benefits to children's health and wellbeing in schools. Therefore, this study aims to determine the potential benefits of horticultural activity for children from both psychological and physiological perspectives. Twenty-six elementary school students (mean age, 8.12 ± 0.21 years) were asked to perform a plant-related task and a mobile game task for 5 min. During both tasks, physiological sensors were used to measure the participants' heart rate variability, skin conductance, and skin temperature. Additionally, the participants' emotional responses were assessed using semantic differential and State - Trait Anxiety Inventory tests immediately after each task. Results revealed that, compared with the mobile game task, participants' health statuses were positively correlated with the horticultural task, including a considerable decrease in skin conductance and sympathetic nervous activity, together with a marginal increase in parasympathetic nervous activity. Such responses suggested that horticultural activity increased relaxation and decreased feelings of stress. Furthermore, the horticultural activity was associated with a substantial increment in comfort, naturalness, relaxation, and cheerfulness feelings, as well as a significant reduction in depression and a reduction in total anxiety levels. Given these positive benefits, horticultural activity may provide a great contribution to children's healthy life at school, prompt psychological relaxation and minimize mental stress relative to smartphone games.			
025	**Comparing concentration levels and emotional states of children using electroencephalography**	**S O Kim, J E Jeong, ETC**	**Hort Science**	**2021**

	during horticultural and non-horticultural activities
Abstract	This study aimed to compare the brain activity and emotional states of elementary school students during horticultural and nonhorticultural activities. A total of 30 participants with a mean age of 11.4 ± 1.3 years were included. This experiment was conducted at Konkuk University campus in Korea. Participants performed horticultural activities such as harvesting, planting, sowing seeds, and mixing soil. Non-horticultural activities included playing with a ball, solving math problems, watching animation videos, folding paper, and reading a book. On completion of each activity, participants answered a subjective emotion questionnaire using the semantic differential method (SDM). Results showed that relative theta (RT) power spectrum was significantly lower in both prefrontal lobes of participants when engaged in harvesting and reading a book. The relative mid beta (RMB) power spectrum was significantly higher in both prefrontal lobes when participants engaged in harvesting and playing with a ball. The ratio of the RMB power spectrum to the RT power spectrum reflects concentration. This ratio increased during harvesting activity, indicating that children's concentration also increased. The sensorimotor rhythm (SMR) from mid beta to theta (RSMT), another indicator of concentration, was significantly higher in the right prefrontal lobe during harvesting than during other activities. Furthermore, SDM results showed that the participants felt more natural and relaxed when performing horticultural activities than non-horticultural activities. Horticultural activities may improve brain activity and psychological relaxation in children. Harvesting activity was most effective for improving children's concentration compared with non-horticultural activities.

EXPOSURE TO THE ENVIRONMENTAL MICROBIOME

Exposure to microbes associated with plants, soil and the air around them has a profound impact on gut health. Less than 8 per cent of our gut composition is now thought to be due to genetic inheritance; the rest is due to our lifestyle and the environment.

A strong biological link to nature and the requirement for microbial input from the environment to drive immuno-regulation is a major component of the beneficial effect of green space. Children playing outside leads to increased levels of cytokines and T cells which help prevent autoimmune conditions, IBS, coeliac disease and increases the diversity of microbiota on the skin and in the gut.

During the potential 60 year lifespan, how do Lime Down Solar propose to manage and ameliorate biodiversity across the ancient pastures of North Wiltshire so as not to be responsible for a neglected and unbalanced ecosystem throughout the 2,220 acre greenspace.

Declining biodiversity can increase the risk to humanity from chronic diseases and thereby cause a major public health problem. Without well

considered advanced planning, the disruption to the current diverse natural environment caused by the long term development of the Lime Down Solar site, may result in a lack of regular exposure to the wide range of microbes that are essential for our well-being, and help maintain or restore a healthy gut microbiome.

026	**Biodiversity intervention enhances immune regulation and health associated commensal microbiota among daycare children**	**M I Roslund et al**	**Science Advances**	**2020**
Abstract	As the incidence of immune-mediated diseases has increased rapidly in developed societies, there is an unmet need for novel prophylactic practices to fight against these maladies. This study is the first human intervention trial in which urban environmental biodiversity was manipulated to examine its effects on the commensal microbiome and immunoregulation in children. We analysed changes in the skin and gut microbiota and blood immune markers of children during a 28-day biodiversity intervention. Children in standard urban and nature-oriented daycare centres were analysed for comparison. The intervention diversified both the environmental and skin Gammaproteobacterial communities, which, in turn, were associated with increases in plasma TGF-β1 levels and the proportion of regulatory T cells. The plasma IL-10:IL-17A ratio increased among intervention children during the trial. Our findings suggest that biodiversity intervention enhances immunoregulatory pathways and provide an incentive for future prophylactic approaches to reduce the risk of immune-mediated diseases in urban societies.			

027	**What is the healthy gut microbiota composition? A changing ecosystem across age, environment, diet, and diseases & The gut microbiome in hypertension: recent advances and future perspectives**	**Rinninella & EG Avery et al**	**Circulation Research**	**2021**
Abstract	Each individual is provided with a unique gut microbiota profile that plays many specific functions in host nutrient metabolism, maintenance of structural integrity of the gut mucosal barrier, immunomodulation, and protection against pathogens. Gut microbiota are composed of different bacteria species taxonomically classified by genus, family, order, and phyla. Each human's gut microbiota are shaped in early life as their composition depends on infant transitions (birth gestational date, type of delivery, methods of milk feeding, weaning period) and external factors such as antibiotic use.			

	Accordingly, there is not a unique optimal gut microbiota composition since it is different for each individual. However, a healthy host–microorganism balance must be respected in order to optimally perform metabolic and immune functions and prevent disease development. This review will provide an overview of the studies that focus on gut microbiota balances in the same individual and between individuals and highlight the close mutualistic relationship between gut microbiota variations and diseases. Indeed, dysbiosis of gut microbiota is associated not only with intestinal disorders but also with numerous extra-intestinal diseases such as metabolic and neurological disorders. Understanding the cause or consequence of these gut microbiota balances in health and disease and how to maintain or restore a healthy gut microbiota composition should be useful in developing promising therapeutic interventions.			
028	**The human microbiome**	**HS Blum**	**Advances in Medical Sciences**	**2017**
Abstract	Until recently, human microbiology was based on the identification of single microbes, such as bacteria, fungi and viruses, frequently isolated from patients with acute or chronic infections. Novel culture-independent molecular biochemical analyses (genomics, transcriptomics, proteomics, metabolomics) allow today to detect and classify the diverse microorganisms in a given ecosystem (microbiota), such as the gastrointestinal tract, the skin, the airway system, the urogenital tract and others, and to assess all genomes in these ecosystems (microbiome) as well as their gene products. These analyses revealed that each individual has its own microbiota that plays a role in health and disease. In addition, they greatly contributed to the recent advances in the understanding of the pathogenesis of a wide range of human diseases. It is to be expected that these new insights will translate into diagnostic, therapeutic and preventive measures in the context of personalized/precision medicine.			
029	**Natural Immunity: biodiversity loss and inflammatory diseases are two global megatrends that might be related**	**L Von Hertzen, I Hanski & T Haahtela**	**EMBO Reports**	**2011**
Abstract	We are witnessing two global and deeply worrying trends that, at first glance, seem unrelated. The first trend is the ongoing decline in biodiversity, which is caused by human actions. It could well become the sixth mass extinction of animal and plant species on Earth, comparable in magnitude with the fifth mass extinction at the end of the Cretaceous, 65 million years			

	ago. The second trend is a rapid increase in chronic diseases that are associated with inflammation, especially in developed countries. Inflammation is a key attribute in asthma and allergic diseases, autoimmune diseases and many cancers; even depression has been associated with the presence of inflammatory markers. In this article, we argue that these two phenomena are more closely related than commonly thought: declining biodiversity might actually increase the risk to humanity from chronic diseases and thereby cause a major public health problem.

030	**Regulation of the immune system by biodiversity from the natural environment: an ecosystem service essential to health**	**G A Rook**	**Proceedings of the National Academy of Sciences**	**2013**

Abstract	Epidemiological studies suggest that living close to the natural environment is associated with long-term health benefits including reduced death rates, reduced cardiovascular disease, and reduced psychiatric problems. This is often attributed to psychological mechanisms, boosted by exercise, social interactions, and sunlight. Compared with urban environments, exposure to green spaces does indeed trigger rapid psychological, physiological, and endocrinological effects. However, there is little evidence that these rapid transient effects cause long-term health benefits or even that they are a specific property of natural environments. Meanwhile, the illnesses that are increasing in high-income countries are associated with failing immunoregulation and poorly regulated inflammatory responses, manifested as chronically raised C-reactive protein and proinflammatory cytokines. This failure of immunoregulation is partly attributable to a lack of exposure to organisms (“Old Friends”) from mankind’s evolutionary past that needed to be tolerated and therefore evolved roles in driving immunoregulatory mechanisms. Some Old Friends (such as helminths and infections picked up at birth that established carrier states) are almost eliminated from the urban environment. This increases our dependence on Old Friends derived from our mothers, other people, animals, and the environment. It is suggested that the requirement for microbial input from the environment to drive immunoregulation is a major component of the beneficial effect of green space, and a neglected ecosystem service that is essential for our well-being. This insight will allow green spaces to be designed to optimize health benefits and will provide impetus from health systems for the preservation of ecosystem biodiversity.

Lime Down Solar – Overview of Research Papers on Health Impacts as requested by the Planning Inspectorate 300626

OVERVIEW

'Good Nature' is a recently published book (2024) that I highly recommend reading as an excellent resource and summary of many of the papers that are referenced below and whose content is 100% relevant when considering the longterm potential health implications of Lime Down Solar.
It is authored by Kathy Willis, Professor of Biodiversity, University of Oxford; cross bench peer in the House of Lords; and ex Director of Science at the Royal Botanic Gardens, Kew.

NOTE
The papers cited below are a small selection of the hundreds of research articles and clinical data that I have read over the last 20 years that draw well founded scientific / medical / health conclusions regarding the myriad positive impacts of nature on the wellbeing, vitality and healing journey of the clients / patients with whom we come in to contact on a daily basis.

Due to the proposed 60 year plus lifespan of Lime Down Solar, I have focussed on the detrimental effects such a scheme would have on the 20,000 children's lives that would be adversely affected by such a huge project, inappropriately sited on 2,220 acres of beautiful green space and farmland surrounding the rural communities of North Wiltshire.

KEY
Index = Papers attached as pdf (where available to the public)
Year = Year of Publication

Abstracts of each paper by the author(s) are noted in the accompanying document 'Lime Down Solar - Research Papers & Abstracts'

Index	Paper	Author(s)	Journal	Year	Link
GENERAL OVERVIEW PAPERS In the Lime Down Solar planning application there are limited details of how Lime Down Solar are demonstrating that people will continue to have access to adequate greenspace within the 2,220 acres of solar panels. There is a general commitment to biodiversity net gain and connectivity, yet the various impacts of health, vitality, wellbeing and specifically cognitive development and mental health are barely touched upon.					
001 Details of Paper	**Annual Review of Public Health**	**T Hartig, R Mitchell, S de Vries & H Frumkin**	**Nature and Health**	**2014**	35(1), 207–228 www.annualreviews.org/content/journals/10.1146/annurev-publhealth-032013-182443
002 Details of	**Growing up green:**	**Nadav L. Sprague et al**	**Nature Journal of Exposure**	**2022**	www.nature.com/articles/s41370-022-00445-6

Paper	**A systematic review of the influence of greenspace on youth development and health outcomes**		**Science & Environmental Epidemiology**		
003 Details of Paper	**Greenspace and health, wellbeing, physical activity, and development in children and adolescents:** **An overview of the systematic reviews**	**Mohammad Javad Zare Sakhvidi et al**	**Science**	**2023**	www.sciencedirect.com/science/article/pii/S2468584423000053
004 Details of Paper	**Nature and Children's Health:** **A Systematic Review**	**Amber L Fyfe-Johnson et al**	**PubMed**	**2021**	https://pubmed.ncbi.nlm.nih.gov/34588297/
005 Details of Paper	**Effects of Nature (Greenspace) on Cognitive Functioning in School Children and Adolescents:** **A Systematic Review**	**Dianne A. Vella-Brodrick**	**Nature Educational Psychology Review**	**2022**	https://link.springer.com/article/10.1007/s10648-022-09658-5
THE IMPACT OF GREENNESS AND TREES ON HEALTH What consideration have Lime Down Solar given during the pre construction phase to replacing the volume and, critically, the maturity of trees and hedgerows that will be decimated by the large area to be covered in solar panels. Where is the written evidence to show that Lime Down Solar have systematically reviewed the scale of the implications of their planning application on both the short term and long term health and wellbeing of the surrounding population, specifically on mental health, cognitive ability and levels of stress in relation to the light industrialisation / urbanisation vs current farmland, rolling countryside vistas & abundance of green landscapes of North Wiltshire.					
006 Details of Paper	**Residential greenness and prevalence of major depressive disorders: a cross- sectional, observational, associational study of 94,879 adult UK BioBank participants**	**C Sarkar, C Webster, & J Gallacher**	**The Lancet Planetary Health**	**2018**	2, e162 – e173 www.sciencedirect.com/science/article/pii/S2542519618300512
007	**Impact of Views to school**	**D Li, & WC**	**Landscape and Urban**	**2016**	148, pp149-58

Details of Paper	**landscapes on recovery from stress and mental fatigue**	[redacted]	**Planning**		[redacted]
008 Details of Paper	**Green spaces and cognitive development in primary schoolchildren**		**Proceedings of the National Academy of Sciences**	**2015**	112, pp 7,937 – 7,942 www.pnas.org/doi/10.1073/pnas.1503402112
009 Details of Paper	**The restorative benefits of nature: Toward an integrative framework**		**Journal of Environmental Psychology**	**1995**	15, pp 169 – 82 [redacted]
010 Details of Paper	**Why viewing nature is more fascinating and restorative than viewing buildings:** **A closer look at perceived complexity**		**Urban Forestry & Urban Greening**	**2016**	20, pp 397 – 401 [redacted]

TO THRIVE, THE HUMAN BODY NEEDS GREENNESS & COLOURS / SMELLS OF NATURE

Lime Down Solar would cover 2,220 acres with inert grey black reflective structures of large solar panels releasing toxic VOCs in to the atmosphere vs health enhancing VOCs from conifers and trees. What mitigation factors have been considered to remove dense clouds of toxins from the air, particularly as the solar panels degrade.

How much greenness of nature will be visible vs black/grey of mechanical and metallic structures across the Lime Down Solar site. Fencing should be green and brown, and made of wooden or other natural materials, that have proven beneficial calming effects.

How will the depletion of beneficial terpenes be mitigated so the site will not have detrimental affects on the body's natural killer (NK) cells, resulting in weakened immune systems and chronic health issues.

011 Details of Paper	**Visual colour perception in green exercise: Positive effects on mood and perceived exertion**	[redacted]	**Environmental Science & Technology**	**2012**	46, pp 8,661 -8,666 [redacted]
012	**The processing of colour**	[redacted]	**Neuroimage**	**2019**	191, pp 529-536

Details of Paper	**preference in the brain**	[redacted]			[redacted]
013 Details of Paper	**Conifer derived monoterpenes and forest walking**		**Mass Spectrometry**	**2015**	4, A0042 [redacted]
014 Details of Paper	**Health effects of a forest environment on natural killer cells in humans:** **An observational pilot study**		**Oncotarget**	**2018**	9, 16,501 [redacted]

THE IMPACT OF SOUNDS OF NATURE vs MECHANICAL NOISE ON HEALTH

There is a large body of evidence regarding the strong negative impact of certain mechanical and electrical sounds on health vs. natural sounds that help in alleviating stress, restoring vitality and relieving pain.

In the construction phase how are Lime Down Solar going to ensure that reasonable hours of work operation are being enforced without juggernauts rumbling down narrow country lanes, lorries beeping on site when reversing, etc and village homes selected for peace and quiet disturbed daily for 3 years, followed by not insignificant background noise levels in the long term.

Have sonic protection, critical re-housing and respite provisions been included in the plans to allow our most vulnerable children and those with serious health problems to have adequate sleep and quiet study / recovery time.

Has adequate consideration been given to the ornithological impact of the lack of hedgerows and the consequent requirement for significant additional planting to encourage the return of bird species to the area after the construction phase, and thus mitigate the initial negative effect on the current restorative human environment across the nine villages that would be effected.

015 Details of Paper	**Restorative qualities of and preference for natural or urban soundscapes**	[redacted]	**rontiers in sychology**	**2017**	8, 1705 https://pmc.ncbi.nlm.nih.gov/articles/PMC5632731/
016 Details of Paper	**Predicting the restorative potential of bird sounds through acoustics and aesthetics**		**nvironment & ehaviour**	**2020**	52, pp 371-400 [redacted]

		[redacted]			ustics_and_Aesthetics
017 Details of Paper	**Associations with bird sounds: How do they relate to perceived restorative potential ?**		**Journal of Environmental Psychology**	**2016**	47, pp 136 – 144 https://doi.org/10.1016/j.jenvp.2016.5.009 [redacted]
018 Details of Paper	**Of cricket chirps and car horns: The effect of nature sounds on cognitive performance**		**Psychonomic Bulletin & Review**	**2019**	26, pp522 – 530, https://doi.org/10.3758/s13423-018-1539-1
019 Details of Paper	**A synthesis of health benefits of natural sounds and their distribution in national parks**		**Proceedings of the National Academy of Sciences**	**2021**	118, e2013097118
020 Details of Paper	**Urban greenspace soundscapes and their perceived restorativeness**		**People and Nature**	**2021**	3, pp756 – 769 [redacted]

THE BENEFITS OF HORTICULTURE & TOUCHING NATURE

Horticultural therapy is a well recognised occupational health intervention for both physical wellbeing and mental health conditions, depression, ADHD, autism and, in addition, memory loss in older people. Touching live plants is proven to have a calming effect on the central nervous system. Walking barefoot in nature induces physiological calming and psychological relaxation compared with marble, concrete etc.

Should the current planning application be successful, it would result in the loss of a large swathe of countryside to solar panels and BESS units, and the erection of high fencing throughout the thousands of acres of the site.

What factors have been considered and what provisions made by Lime Down Solar for children to continue to benefit from free access to their local countryside, which is known to help minimise mental stress and significantly promote wellbeing vs staying indoors and using smartphones, and enables them to participate in horticultural and associated nature based activities that improve brain activity, help concentration and promote psychological relaxation.

021 Details of Paper	**Assessment of the psychpathological effects of a horticultural therapy programme in patients with schizophrenia**	[redacted]	**Complementary Therapies in Medicine**	**2018**	36, pp 54-8 [redacted]

022 Details of Paper	**Psychological & Physiological effect in humans of touching plant foliage – cerebral activity as indicators**	[redacted]	**Journal of Physiological Anthropology**	**2013**	32, pp 1-9 [redacted] 6805-32-7
023 Details of Paper	**Physiological effects of touching the wood of hinoki cypress trees with the soles of the feet**		**International Journal of environmental Research and Public Health**	**2018**	[redacted] s10086-017-1691-7
024 Details of Paper	**Horticultural activity: Its contribution to stress recovery and wellbeing for children**		**International Journal of environmental Research and Public Health**	**2020**	17, 1229 [redacted]
025 Details of Paper	**Comparing concentration levels and emotional states of children using electroencephalography during horticultural and non-horticultural activities**		**Hort Science**	**2021**	56, pp 324-9 [redacted]

EXPOSURE TO THE ENVIRONMENTAL MICROBIOME

Exposure to microbes associated with plants, soil and the air around them has a profound impact on gut health. Less than 8 per cent of our gut composition is now thought to be due to genetic inheritance; the rest is due to our lifestyle and the environment.

A strong biological link to nature and the requirement for microbial input from the environment to drive immuno-regulation is a major component of the beneficial effect of green space. Children playing outside leads to increased levels of cytokines and T cells which help prevent autoimmune conditions, IBS, coeliac disease and increases the diversity of microbiota on the skin and in the gut.

During the potential 60 year lifespan, how do Lime Down Solar propose to manage and ameliorate biodiversity across the ancient pastures of North Wiltshire so as not to be responsible for a neglected and unbalanced ecosystem throughout the 2,220 acre greenspace.

Declining biodiversity can increase the risk to humanity from chronic diseases and thereby cause a major public health problem. Without well considered advanced planning, the disruption to the current diverse natural environment caused by the long term development of the Lime Down Solar site, may result in a lack of regular exposure to the wide range of microbes that are essential for our well-being, and help maintain or restore a healthy gut microbiome.

026 Details of	**Biodiversity intervention enhances immune regulation and health**	[redacted]	**Science Advances**	**2020**	6, eaba2578 [redacted]

Paper	**associated commensal microbiota among daycare children**	[redacted]			[redacted]
027 Details of Paper	**What is the healthy gut microbiota composition? A changing ecosystem across age, environment, diet, and diseases & The gut microbiome in hypertension: recent advances and future perspectives**		**Circulation Research**	**2021**	128, pp 934-50 [redacted]
028 Details of Paper	**The human microbiome**		**Advances in Medical Sciences**	**2017**	62, 99 414-20 [redacted]
029 Details of Paper	**Natural Immunity: biodiversity loss and inflammatory diseases are two global megatrends that might be related**		**EMBO Reports**	**2011**	12, 1,089-93 [redacted]
030 Details of Paper	**Regulation of the immune system by biodiversity from the natural environment: an ecosystem service essential to health**		**Proceedings of the National Academy of Sciences**	**2013**	110, pp 18,260-7 www.pnas.org/doi/10.1073/pnas.1313731110

The book ‘Good Nature’ by Professor Kathy Willis and the selection of papers cited above (and attached) are some of the more relevant scientific papers regarding the impact of nature and the access to greenspace on children's development, cognitive, mental and physical, that should be understood and thoroughly reviewed in advance of the Lime Down Solar project being further considered.

CONFIDENTIAL
FORMATTING NOTE

The narrow final column has book references to [redacted] publication ‘Good Nature’
The text of these is in WHITE so is not visible in the Final PDF

Lime Down Solar - Research Papers on Health Impacts as requested by the Planning Inspectorate 300626

RESEARCH PAPERS and ABSTRACTS

To be read in conjunction with accompanying document 'Overview of Research Papers on Health Impacts for the Planning inspectorate'.

NOTE
The papers cited below are a small selection of the hundreds of research articles and clinical data that I have read over the last 20 years that draw well founded scientific / medical / health conclusions regarding the myriad positive impacts of nature on the wellbeing, vitality and healing journey of the clients / patients with whom we come in to contact on a daily basis.

Due to the proposed 60 year plus lifespan of Lime Down Solar, I have focussed on the detrimental effects such a scheme would have on the 20,000 children's lives that would be adversely affected by such a huge project, inappropriately sited on 2,220 acres of beautiful green space and farmland surrounding the rural communities of North Wiltshire.

KEY
Index = Papers attached as pdf (where available to the public)
Abstract = Overview of each paper by the author(s)

Index	Paper	Author(s)	Journal	Year of Publication
GENERAL OVERVIEW PAPERS In the Lime Down Solar planning application there are limited details of how Lime Down Solar are demonstrating that people will continue to have access to adequate greenspace within the 2,220 acres of solar panels. There is a general commitment to biodiversity net gain and connectivity, yet the various impacts of health, vitality, wellbeing and specifically cognitive development and mental health are barely touched upon.				
001	**Annual Review of Public Health**	[redacted]	**Nature and Health**	**2014**
Abstract	Urbanization, resource exploitation, and lifestyle changes have diminished possibilities for human contact with nature in many societies. Concern about the loss has helped motivate research on the health benefits of contact with nature. Reviewing that research here, we focus on nature as represented by aspects of the physical environment relevant to planning, design, and policy measures that serve broad segments of urbanized societies. We discuss difficulties in defining "nature" and reasons for the current expansion of the research field, and we assess available reviews. We then consider research on pathways between nature and health involving air quality, physical activity, social cohesion, and stress			

	reduction. Finally, we discuss methodological issues and priorities for future research. The extant research does describe an array of benefits of contact with nature, and evidence regarding some benefits is strong.			
002	**Growing up green:** **A systematic review of the influence of greenspace on youth development and health outcomes**	[redacted]	**Nature** **Journal of Exposure Science & Environmental Epidemiology**	**2022**
Abstract	Youth growing up in places with more greenspaces have better developmental outcomes. The literature on greenspace and youth development is largely cross-sectional, thus limited in terms of measuring development and establishing causal inference. We conducted a systematic review of prospective, longitudinal studies measuring the association between greenspace exposure and youth development outcomes measured between ages two and eighteen. Study quality was assessed using a 10-item checklist adapted from a previously published review on greenspace and health. Twenty-eight studies met criteria for review and were grouped into five thematic categories based on reported outcomes: - cognitive and brain development, - mental health and wellbeing, - attention and behaviour, - allergy and respiratory, and - obesity and weight. 79% of studies suggest an association between greenspace and improved youth development.			
003	**Greenspace and health, wellbeing, physical activity, and development in children and adolescents:** **An overview of the systematic reviews**	[redacted]	**Science**	**2023**
Abstract	The evidence on the beneficial association of greenspace exposure and mental and physical health and wellbeing of children and adolescents is accumulating.			

	We systematically searched PubMed, Scopus, and Web of Science for systematic reviews and/or meta-analyses on health, developmental, and behavioural outcomes in children and adolescents related to greenspace exposure, published until August 2022. Most of the available reviews are on mental health and behavioural outcomes. Overall, reviews are suggestive of a beneficial association of greenspace with a range of outcomes *e.g.*, birth, neurodevelopmental, cognitive, behavioural, weight-related, mental health and wellbeing, school performance, and physical and outdoor activities), except for allergic and respiratory outcomes for which the evidence is not conclusive.			
004	**Nature and Children's Health:** **A Systematic Review**	[redacted]	**PubMed**	**2021**
Abstract	Current literature supports a positive relationship between nature contact and children's health, especially for physical activity and mental health, both public health priorities. The evidence supports paediatricians in advocating for equitable nature contact for children in places where they live, play, and learn.			
005	**Effects of Nature (Greenspace) on Cognitive Functioning in School Children and Adolescents: A Systematic Review**	[redacted]	**Nature Educational Psychology Review**	**2022**
Abstract	There is growing interest in understanding the extent to which natural environments can influence learning particularly in school contexts. Nature has the potential to relieve cognitive overload, reduce stress and increase wellbeing - all factors that are conducive to learning. This paper provides a PRISMA-guided systematic review of the literature examining the effects of nature interventions on the cognitive functioning of young people aged 5 to 18 years. Examples of nature interventions include outdoor learning, green playgrounds, walks in nature, plants in classrooms and nature views from classroom windows. These can vary in duration and level of interaction (passive or active). Results provide substantial support for cognitive benefits of nature interventions regarding selective attention, sustained attention and working memory. Underlying mechanisms for the benefits were also explored, including enhanced wellbeing, cognitive restoration and stress reduction - all likely to be contributors to the nature-cognition relationship. <u>Introduction</u>: The pressure of modern-day westernized living involving technology, high-rise buildings, traffic congestion and pollution is taking a toll on society.			

These lifestyle changes have led to reduced opportunities for interacting with nature (Hartig et al., 2014) and a fast-paced lifestyle that can be psychologically draining.

Subsequently health and well-being are compromised as evidenced by escalating rates of mental illness (Blake et al., 2018; Michaelson et al., 2020; Vancampfort et al., 2018).

In an attempt to reduce fatigue and improve well-being, research attention has turned to the potential healing effects of nature (Capaldi et al, 2015; Diaz et al., 2015; Hartig et al. 2014).

THE IMPACT OF GREENNESS AND TREES ON HEALTH

What consideration have Lime Down Solar given during the pre construction phase to replacing the volume and, critically, the maturity of trees and hedgerows that will be decimated by the large area to be covered in solar panels.

Where is the written evidence to show that Lime Down Solar have systematically reviewed the scale of the implications of their planning application on both the short term and long term health and wellbeing of the surrounding population, specifically on mental health, cognitive ability and levels of stress in relation to the light industrialisation / urbanisation vs current farmland, rolling countryside vistas & abundance of green landscapes of North Wiltshire.

006	**Residential greenness and prevalence of major depressive disorders: a cross- sectional, observational, associational study of 94,879 adult UK BioBank participants**	[redacted]	**The Lancet Planetary Health**	**2018**
Abstract	Increased urbanisation and the associated reduced contact of individuals with natural environments have led to a rise in mental disorders, including depression. Residential greenness, a fundamental component of urban design, has been shown to reduce the public health burden of mental disorders. The present study investigates the association between residential green exposure and prevalence of major depressive disorders using a large and diverse cross-sectional dataset from the UK Biobank.			

007	**Impact of Views to school landscapes on recovery from stress and mental fatigue**	[redacted]	**Landscape and Urban Planning**	**2016**
Abstract	Previous research has demonstrated positive associations between the greenness of high school landscapes and school wide academic performance.			

	We hypothesize that views onto green landscapes help students recover from mental fatigue and stress. Participants were randomly assigned to classrooms without windows or with windows that opened onto a built space or a green space. Participants engaged in typical classroom activities followed by a break in the classroom to which they were assigned. Results demonstrate that classroom views to green landscapes cause significantly better performance on tests of attention and increase student's recovery from stressful experiences. A lack of mediation effect demonstrates that attention restoration and stress recovery are two distinct processes. Implications for school site selection, design and renovation are discussed.			
008	**Green spaces and cognitive development in primary schoolchildren**	[redacted]	**Proceedings of the National Academy of Sciences**	**2015**
Abstract	Green spaces have a range of health benefits, but little is known in relation to cognitive development in children. This study, based on comprehensive characterization of outdoor surrounding greenness (at home, school, and during commuting) and repeated computerized cognitive tests in schoolchildren, found an improvement in cognitive development associated with surrounding greenness, particularly with greenness at schools. This association was partly mediated by reductions in air pollution. Our findings provide policymakers with evidence for feasible and achievable targeted interventions such as improving green spaces at schools to attain improvements in mental capital at population level.			
009	**The restorative benefits of nature: Toward an integrative framework**	[redacted]	**Journal of Environmental Psychology**	**1995**
Abstract	Directed attention plays an important role in human information processing; its fatigue, in turn, has far-reaching consequences. Attention Restoration Theory provides an analysis of the kinds of experiences that lead to recovery from such fatigue. Natural environments turn out to be particularly rich in the characteristics necessary for restorative experiences. An integrative framework is proposed that places both directed attention and stress in the larger context of human-environment relationships.			
010	**Why viewing nature is more fascinating and restorative than viewing buildings:** **A closer look at perceived complexity**	[redacted]	**Urban Forestry & Urban Greening**	**2016**

Abstract	The present paper addresses the question which visual features trigger people's often more positive affective responses to natural compared to built scenes. Building on notions about visual complexity and fractal geometry, we propose that perceived complexity of magnified scene parts can predict the greater fascinating and restorative qualities of natural versus built scenes. This prediction was tested in an experiment in which 40 participants viewed and rated 40 images of unspectacular natural and built scenes in their original size, and at 400% and 1600% magnification levels. Results showed that the original, unmagnified natural scenes were viewed longer and rated more restorative than built scenes, and that these differences were statistically mediated by the greater perceived complexity of magnified parts of natural scenes. These findings fit with the idea that fractal-like, recursive complexity is an important visual cue underlying the restorative potential of natural and built environments.

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How much greenness of nature will be visible vs black/grey of mechanical and metallic structures across the Lime Down Solar site. Fencing should be green and brown, and made of wooden or other natural materials, that have proven beneficial calming effects.

How will the depletion of beneficial terpenes be mitigated so the site will not have detrimental affects on the body's natural killer (NK) cells, resulting in weakened immune systems and chronic health issues.

011	**Visual colour perception in green exercise: Positive effects on mood and perceived exertion**	[redacted]	**Environmental Science & Technology**	**2012**

Abstract	A significant interaction between test time and colour perception indicated that anger decreased in the two green colour conditions. A significant interaction of colour perception by form perception by test time was associated with a significant decrease in response times on the attention task after cycling among participants who viewed the green tree. Our findings are important for interpreting mechanisms underlying characteristics attributable to environmental benefits and revealed that single (colour or form) or combined (colour and form) visual perception improved the mental health benefits of exercise.

	These findings may also inform the design and planning of urban green spaces to maximize green exercise effects.			
012	**The processing of colour preference in the brain**	[redacted]	**Neuroimage**	**2019**
Abstract	We looked for correlations of a behavioural measure of colour preference with the blood oxygen level-dependent (BOLD) response when participants performed an irrelevant orientation judgement task on coloured squares. A whole brain analysis found a significant correlation between BOLD activity and colour preference in the posterior midline cortex (PMC), centred on the precuneus but extending into the adjacent posterior cingulate and cuneus. These results demonstrate that brain activity is modulated by colour preference, even when such preferences are irrelevant to the ongoing task the participants are engaged. They also suggest that colour preferences automatically influence our processing of the visual world. Interestingly, the effect in the PMC overlaps with regions identified in neuroimaging studies of preference and value judgements of other types of stimuli. Therefore, our findings extends this literature to show that the PMC is related to automatic encoding of subjective value even for basic visual features such as colour.			
013	**Conifer derived monoterpenes and forest walking**	[redacted]	**Mass Spectrometry**	**2015**
Abstract	Conifer and broadleaf trees emit volatile organic compounds in the summer. The major components of these emissions are volatile monoterpenes. Using solid phase micro extraction fibre as the adsorbent, monoterpenes were successfully detected and identified in forest air samples. Gas chromatography / mass chromatogram of monoterpenes in the atmosphere of a conifer forest and that of serum from subjects who were walking in a forest were found to be similar each other. The amounts of α-pinene in the subjects became several folds higher after forest walking. The results indicate that monoterpenes in the atmosphere of conifer forests are transferred to and accumulate in subjects by inhalation while they are exposed to this type of environment.			
014	**Health effects of a forest environment on natural killer cells in humans:**	[redacted]	**Oncotarget**	**2018**

	An observational pilot study			
Abstract	Health effect assessments based on natural killer (NK) cells are an important emerging area of human health. We recruited 90 forest staff members in Xitou, Taiwan and 110 urban staff members in Taipei to investigate the health effects of forest environment exposure on NK cells (CD3−/CD56+) and activating NK cells (CD3−/CD56+/CD69+) in humans. We also invited 11 middle-aged volunteers in a pilot study to participate in a five-day/four-night forest trip to Xitou forest to investigate the health effects of a forest trip on NK cells and activating NK cells. Results showed that NK cells were higher in the forest group (19.5 ± 9.1%) than in the urban group (16.4 ± 8.4%). In particular, the percentage of NK cells was significantly higher in the forest group than in the urban group among the subgroups of male, a higher body mass index (≥ 25 kg/m2), without hypertension, lower high-sensitivity C-reactive protein, hyperglycaemia, without smoking habit, and with tea drinking habit. This study suggests that exposure to forest environments might enhance the immune response of NK cells and activating NK cells in humans.			

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In the construction phase how are Lime Down Solar going to ensure that reasonable hours of work operation are being enforced without juggernauts rumbling down narrow country lanes, lorries beeping on site when reversing, etc and village homes selected for peace and quiet disturbed daily for 3 years, followed by not insignificant background noise levels in the long term.

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Has adequate consideration been given to the ornithological impact of the lack of hedgerows and the consequent requirement for significant additional planting to encourage the return of bird species to the area after the construction phase, and thus mitigate the initial negative effect on the current restorative human environment across the nine villages that would be effected.

015	**Restorative qualities of and preference for natural or urban soundscapes**	[redacted]	**Frontiers in psychology**	**2017**

Abstract	Psychological restoration in urban agglomerations has become a growing challenge. Although scientific proof of the significance of nature is irrefutable, an increase in built-up areas has led to a decrease in urban greenery. Thus, a growing need for restorativeness in urban surroundings has emerged. To investigate whether positively evaluated sonic environments, represented by natural and urban sounds, have comparable restorative qualities we conducted two studies. The aim of the first (Study 1) was to explore the restorative qualities of positively assessed natural and urban sounds. Participants (*N* = 88) were asked to listen and to rate 22 recordings (each 1 min long) either from natural or urban environments. In the second (Study 2) we investigated whether positively evaluated sonic environments (natural and urban), demand for restoration (feeling relaxed or fatigued) and company (being alone or with a friend) affect the restorative qualities of natural and urban soundscapes… Our findings confirmed that natural sounds are perceived more favourably than urban recordings. Even when only the most positively assessed soundscapes were compared, nature was still perceived as being more restorative than urban areas.

016	**Predicting the restorative potential of bird sounds through acoustics and aesthetics**		**Environment & Behaviour**	**2020**

Abstract	Some, but not all, bird sounds are associated with perceptions of restoration from stress and cognitive fatigue. In this online study, ratings of perceived restorative potential (PRP) and aesthetic properties of 50 bird sounds were provided by 174 residents of the United Kingdom. Regression analyses demonstrated that sound level, harmonics, and frequency, and perceptions of complexity, familiarity, and pattern, were significant predictors of PRP and cognitive and affective appraisals of bird sounds. These findings shed light on the structural and perceptual properties that may influence restorative potential of acoustic natural stimuli. Finally, through their potential associations with meaning, these findings highlight the importance of further study of semantic or meaning-based properties within the restorative environments literature.

017	**Associations with bird sounds: How do they relate to perceived restorative potential ?**		**Journal of Environmental Psychology**	**2016**

Abstract	Bird sounds are related to perceptions of attention restoration and stress recovery, but the role of associations in such perceptions is

	understudied. Adult residents of the United Kingdom rated bird sounds on perceived restorative potential (PRP) and provided qualitative data on associations with each sound. Bird sounds were associated with imagined environments, birds and other animals, time and season, and activities within the environment. Bird sounds rated as high in PRP were associated with green spaces, spring and summer, daytime, and active behaviours in the environment. Low-PRP bird sounds were associated with exotic and marine environments, non-avian animals, and showed a non-significant trend towards associations with negative bird behaviour. These findings highlight connections between semantic values and restorative perceptions of natural stimuli. Such connections can inform top-down approaches to study of restorative environments and may benefit conservationists seeking to improve bonds between people and wildlife.

018	**Of cricket chirps and car horns: The effect of nature sounds on cognitive performance**	[redacted]	**Psychonomic Bulletin & Review**	**2019**

Abstract	Attention restoration theory (ART) posits that stimuli found in nature may restore directed attention functioning by reducing demands on the endogenous attention system. In the present experiment, we assessed whether nature-related cognitive benefits extended to auditory presentations of nature, a topic that has been understudied. To assess directed attention, we created a composite measure consisting of a backward digit span task and a dual n-back task. Participants completed these cognitive measures and an affective questionnaire before and after listening to and aesthetically judging either natural or urban soundscapes (between-participants). Relative to participants who were exposed to urban soundscapes, we observed significant improvements in cognitive performance for individuals exposed to nature. Urban soundscapes did not systematically affect performance either adversely or beneficially. Natural sounds did not differentially change positive or negative affect, despite these sounds being aesthetically preferred to urban sounds. These results provide initial evidence that brief experiences with natural sounds can improve directed attention functioning in a single experimental session.

019	**A synthesis of health benefits of natural sounds and their distribution in national parks**	[redacted]	**Proceedings of the National Academy of Sciences**	**2021**

Abstract

Parks are important places to listen to natural sounds and avoid human-related noise, an increasingly rare combination.

We first explore whether and to what degree natural sounds influence health outcomes using a systematic literature review and meta-analysis.

Examples of beneficial outcomes include decreased pain, lower stress, improved mood, and enhanced cognitive performance.

Given this evidence, and to facilitate incorporating public health in US national park soundscape management, we then examined the distribution of natural sounds in relation to anthropogenic sound at 221 sites across 68 parks.

National park soundscapes with little anthropogenic sound and abundant natural sounds occurred at 11.3% of the sites. Parks with high visitation and urban park sites had more anthropogenic sound, yet natural sounds associated with health benefits also were frequent.

These included animal sounds (audible for a mean of 59.3% of the time, SD: 23.8) and sounds from wind and water (mean: 19.2%, SD: 14.8).

Urban and other parks that are extensively visited offer important opportunities to experience natural sounds and are significant targets for soundscape conservation to bolster health for visitors.

Our results assert that natural sounds provide important ecosystem services, and parks can bolster public health by highlighting and conserving natural soundscapes.

020	**Urban greenspace soundscapes and their perceived restorativeness**	[redacted]	**People and Nature**	**2021**

Abstract

Past research has largely focused on visual stimuli, yet the auditory pathway is also an important means for contact with nature.

The sonic environments of urban green spaces, however, are rarely entirely natural and many differ in their composition of natural sounds and anthropogenic noise. Few studies have investigated how these differences may impact the restorative potential of these soundscapes and, in particular, how the presence of traffic noise may constrain the benefits of natural sounds.

To address this gap, we examined differences in the perceived restorativeness and perceived restorative outcomes across a gradient of eight park soundscapes that differed in bird and traffic sounds.

	In a laboratory setting, 162 participants listened to sound samples and reported on perceptions of the soundscapes and restorative potential and outcomes. The results strongly indicate that park soundscapes with a rich array of perceived bird sounds and minimal perceived traffic noise offer the greatest perceived restoration. Traffic noise was found to moderate the positive effect of bird sounds. The duration of time lived in the city and noise sensitivity were also positively associated with greater perceived restorative benefits while noise□sensitive people were also more negatively affected by traffic noise. The promotion of highly natural soundscapes in urban green spaces and the reduction of traffic noise can provide nature□based solutions to human health and well□being in urban areas.

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Horticultural therapy is a well recognised occupational health intervention for both physical wellbeing and mental health conditions, depression, ADHD, autism and, in addition, memory loss in older people. Touching live plants is proven to have a calming effect on the central nervous system. Walking barefoot in nature induces physiological calming and psychological relaxation compared with marble, concrete etc.

Should the current planning application be successful, it would result in the loss of a large swathe of countryside to solar panels and BESS units, and the erection of high fencing throughout the thousands of acres of the site.

What factors have been considered and what provisions made by Lime Down Solar for children to continue to benefit from free access to their local countryside, which is known to help minimise mental stress and significantly promote wellbeing vs staying indoors and using smartphones, and enables them to participate in horticultural and associated nature based activities that improve brain activity, help concentration and promote psychological relaxation.

021	**Assessment of the psychpathological effects of a horticultural therapy programme in patients with schizophrenia**	[redacted]	**Complementary Therapies in Medicine**	**2018**
Abstract	A horticultural therapy program improved the scores of schizophrenic patients in the Positive and Negative Syndrome Scale. A horticultural therapy program improved clinical symptoms in the Brief Psychiatric Rating Scale of schizophrenic patients. A horticultural therapy program significantly improved psychopathological symptoms of patients with schizophrenia. This study showed the potential of horticultural therapy for improving psychopathologic symptoms of psychiatric patients.			

022	**Psychological & Physiological effect in humans of touching plant foliage – cerebral activity as indicators**	[redacted]	**Journal of Physiological Anthropology**	**2013**

Abstract

Numerous studies have reported on the healing powers of plants and nature, but there have not been so many instances of experimental research. In particular, there are very few psychological and physiological studies using tactile stimuli.

This study examines the psychological and physiological effects of touching plant foliage by using an evaluation profile of the subjects' impressions and investigating cerebral blood flow.

The fabric stimulus gave people 'soft' and 'rough' impressions, 'kind', 'peaceful' and 'pleasant' feelings psychologically, and a sense of physiological calm.

On the other hand, the metal stimulus gave people 'cold', 'smooth' and 'hard' impressions and an image of something 'artificial'. The metal stimulus caused a stress response in human cerebral blood flow although its evaluation in terms of 'pleasant or unpleasant' was neutral.

There were no remarkable differences between the stimuli of natural and artificial pothos compared with other types of stimulus psychologically. However, only the natural pothos stimulus showed a sense of physiological calm in the same appearance as the fabric stimulus.

This study shows that people experience an unconscious calming reaction to touching a plant. It is to be concluded that plants are an indispensable element of the human environment.

023	**Physiological effects of touching the wood of hinoki cypress trees with the soles of the feet**	[redacted]	**International Journal of environmental Research and Public Health**	**2018**

Abstract

This study aimed to clarify the physiological effects of touching hinoki cypress (hereinafter called "hinoki") (*Chamaecyparis obtusa*) wood with the palm of the right hand on brain activity and autonomic nervous activity.

Twenty-two female university students (mean age 21.1 ± 0.2 years) participated in the study. As an indicator of brain activity, oxyhemoglobin (oxy-Hb) concentrations were measured in the left/right prefrontal cortex using near-infrared time-resolved spectroscopy.

Marble was used as a control material. After sitting at rest with their eyes closed, the participants touched the materials for 90s with their eyes still closed.

The results showed that tactile stimulation with hinoki wood significantly decreased oxy-Hb concentration in the left prefrontal cortex and

	increased ln(HF) reflected parasympathetic nervous activity compared with marble. In conclusion, our study showed that touching hinoki wood with the palm calms prefrontal cortex activity and increases parasympathetic nervous activity, thereby inducing physiological relaxation.			
024	**Horticultural activity: Its contribution to stress recovery and wellbeing for children**	[redacted]	**International Journal of Environmental Research and Public Health**	**2020**
Abstract	In recent years, children's use of mobile phones has grown rapidly, which might lead to an increase in mental stress and negatively affect their health. Despite increasing evidence that horticultural activity can provide significant health benefits, few scientific evidence-based studies are currently available regarding these benefits to children's health and wellbeing in schools. Therefore, this study aims to determine the potential benefits of horticultural activity for children from both psychological and physiological perspectives. Twenty-six elementary school students (mean age, 8.12 ± 0.21 years) were asked to perform a plant-related task and a mobile game task for 5 min. During both tasks, physiological sensors were used to measure the participants' heart rate variability, skin conductance, and skin temperature. Additionally, the participants' emotional responses were assessed using semantic differential and State - Trait Anxiety Inventory tests immediately after each task. Results revealed that, compared with the mobile game task, participants' health statuses were positively correlated with the horticultural task, including a considerable decrease in skin conductance and sympathetic nervous activity, together with a marginal increase in parasympathetic nervous activity. Such responses suggested that horticultural activity increased relaxation and decreased feelings of stress. Furthermore, the horticultural activity was associated with a substantial increment in comfort, naturalness, relaxation, and cheerfulness feelings, as well as a significant reduction in depression and a reduction in total anxiety levels. Given these positive benefits, horticultural activity may provide a great contribution to children's healthy life at school, prompt psychological relaxation and minimize mental stress relative to smartphone games.			
025	**Comparing concentration levels and emotional states of children using electroencephalography**	**S O Kim, J E Jeong, ETC**	**Hort Science**	**2021**

	during horticultural and non-horticultural activities
Abstract	This study aimed to compare the brain activity and emotional states of elementary school students during horticultural and nonhorticultural activities. A total of 30 participants with a mean age of 11.4 ± 1.3 years were included. This experiment was conducted at Konkuk University campus in Korea. Participants performed horticultural activities such as harvesting, planting, sowing seeds, and mixing soil. Non-horticultural activities included playing with a ball, solving math problems, watching animation videos, folding paper, and reading a book. On completion of each activity, participants answered a subjective emotion questionnaire using the semantic differential method (SDM). Results showed that relative theta (RT) power spectrum was significantly lower in both prefrontal lobes of participants when engaged in harvesting and reading a book. The relative mid beta (RMB) power spectrum was significantly higher in both prefrontal lobes when participants engaged in harvesting and playing with a ball. The ratio of the RMB power spectrum to the RT power spectrum reflects concentration. This ratio increased during harvesting activity, indicating that children's concentration also increased. The sensorimotor rhythm (SMR) from mid beta to theta (RSMT), another indicator of concentration, was significantly higher in the right prefrontal lobe during harvesting than during other activities. Furthermore, SDM results showed that the participants felt more natural and relaxed when performing horticultural activities than non-horticultural activities. Horticultural activities may improve brain activity and psychological relaxation in children. Harvesting activity was most effective for improving children's concentration compared with non-horticultural activities.

EXPOSURE TO THE ENVIRONMENTAL MICROBIOME

Exposure to microbes associated with plants, soil and the air around them has a profound impact on gut health. Less than 8 per cent of our gut composition is now thought to be due to genetic inheritance; the rest is due to our lifestyle and the environment.

A strong biological link to nature and the requirement for microbial input from the environment to drive immuno-regulation is a major component of the beneficial effect of green space. Children playing outside leads to increased levels of cytokines and T cells which help prevent autoimmune conditions, IBS, coeliac disease and increases the diversity of microbiota on the skin and in the gut.

During the potential 60 year lifespan, how do Lime Down Solar propose to manage and ameliorate biodiversity across the ancient pastures of North Wiltshire so as not to be responsible for a neglected and unbalanced ecosystem throughout the 2,220 acre greenspace.

Declining biodiversity can increase the risk to humanity from chronic diseases and thereby cause a major public health problem. Without well

considered advanced planning, the disruption to the current diverse natural environment caused by the long term development of the Lime Down Solar site, may result in a lack of regular exposure to the wide range of microbes that are essential for our well-being, and help maintain or restore a healthy gut microbiome.

026	**Biodiversity intervention enhances immune regulation and health associated commensal microbiota among daycare children**	[redacted]	**Science Advances**	**2020**

Abstract

As the incidence of immune-mediated diseases has increased rapidly in developed societies, there is an unmet need for novel prophylactic practices to fight against these maladies.

This study is the first human intervention trial in which urban environmental biodiversity was manipulated to examine its effects on the commensal microbiome and immunoregulation in children.

We analysed changes in the skin and gut microbiota and blood immune markers of children during a 28-day biodiversity intervention. Children in standard urban and nature-oriented daycare centres were analysed for comparison.

The intervention diversified both the environmental and skin Gammaproteobacterial communities, which, in turn, were associated with increases in plasma TGF-β1 levels and the proportion of regulatory T cells. The plasma IL-10:IL-17A ratio increased among intervention children during the trial.

Our findings suggest that biodiversity intervention enhances immunoregulatory pathways and provide an incentive for future prophylactic approaches to reduce the risk of immune-mediated diseases in urban societies.

027	**What is the healthy gut microbiota composition? A changing ecosystem across age, environment, diet, and diseases** **&** **The gut microbiome in hypertension: recent advances and future perspectives**	[redacted]	**Circulation Research**	**2021**

Abstract

Each individual is provided with a unique gut microbiota profile that plays many specific functions in host nutrient metabolism, maintenance of structural integrity of the gut mucosal barrier, immunomodulation, and protection against pathogens.

Gut microbiota are composed of different bacteria species taxonomically classified by genus, family, order, and phyla. Each human's gut microbiota are shaped in early life as their composition depends on infant transitions (birth gestational date, type of delivery, methods of milk feeding, weaning period) and external factors such as antibiotic use.

	Accordingly, there is not a unique optimal gut microbiota composition since it is different for each individual. However, a healthy host–microorganism balance must be respected in order to optimally perform metabolic and immune functions and prevent disease development. This review will provide an overview of the studies that focus on gut microbiota balances in the same individual and between individuals and highlight the close mutualistic relationship between gut microbiota variations and diseases. Indeed, dysbiosis of gut microbiota is associated not only with intestinal disorders but also with numerous extra-intestinal diseases such as metabolic and neurological disorders. Understanding the cause or consequence of these gut microbiota balances in health and disease and how to maintain or restore a healthy gut microbiota composition should be useful in developing promising therapeutic interventions.			
028	**The human microbiome**	[redacted]	**Advances in Medical Sciences**	**2017**
Abstract	Until recently, human microbiology was based on the identification of single microbes, such as bacteria, fungi and viruses, frequently isolated from patients with acute or chronic infections. Novel culture-independent molecular biochemical analyses (genomics, transcriptomics, proteomics, metabolomics) allow today to detect and classify the diverse microorganisms in a given ecosystem (microbiota), such as the gastrointestinal tract, the skin, the airway system, the urogenital tract and others, and to assess all genomes in these ecosystems (microbiome) as well as their gene products. These analyses revealed that each individual has its own microbiota that plays a role in health and disease. In addition, they greatly contributed to the recent advances in the understanding of the pathogenesis of a wide range of human diseases. It is to be expected that these new insights will translate into diagnostic, therapeutic and preventive measures in the context of personalized/precision medicine.			
029	**Natural Immunity: biodiversity loss and inflammatory diseases are two global megatrends that might be related**	[redacted]	**EMBO Reports**	**2011**
Abstract	We are witnessing two global and deeply worrying trends that, at first glance, seem unrelated. The first trend is the ongoing decline in biodiversity, which is caused by human actions. It could well become the sixth mass extinction of animal and plant species on Earth, comparable in magnitude with the fifth mass extinction at the end of the Cretaceous, 65 million years			

	ago. The second trend is a rapid increase in chronic diseases that are associated with inflammation, especially in developed countries. Inflammation is a key attribute in asthma and allergic diseases, autoimmune diseases and many cancers; even depression has been associated with the presence of inflammatory markers. In this article, we argue that these two phenomena are more closely related than commonly thought: declining biodiversity might actually increase the risk to humanity from chronic diseases and thereby cause a major public health problem.

030	**Regulation of the immune system by biodiversity from the natural environment: an ecosystem service essential to health**	[redacted]	**Proceedings of the National Academy of Sciences**	**2013**

Abstract	Epidemiological studies suggest that living close to the natural environment is associated with long-term health benefits including reduced death rates, reduced cardiovascular disease, and reduced psychiatric problems. This is often attributed to psychological mechanisms, boosted by exercise, social interactions, and sunlight. Compared with urban environments, exposure to green spaces does indeed trigger rapid psychological, physiological, and endocrinological effects. However, there is little evidence that these rapid transient effects cause long-term health benefits or even that they are a specific property of natural environments. Meanwhile, the illnesses that are increasing in high-income countries are associated with failing immunoregulation and poorly regulated inflammatory responses, manifested as chronically raised C-reactive protein and proinflammatory cytokines. This failure of immunoregulation is partly attributable to a lack of exposure to organisms (“Old Friends”) from mankind’s evolutionary past that needed to be tolerated and therefore evolved roles in driving immunoregulatory mechanisms. Some Old Friends (such as helminths and infections picked up at birth that established carrier states) are almost eliminated from the urban environment. This increases our dependence on Old Friends derived from our mothers, other people, animals, and the environment. It is suggested that the requirement for microbial input from the environment to drive immunoregulation is a major component of the beneficial effect of green space, and a neglected ecosystem service that is essential for our well-being. This insight will allow green spaces to be designed to optimize health benefits and will provide impetus from health systems for the preservation of ecosystem biodiversity.