HUMAN HEALTH IMPACTS OF LIME DOWN SOLAR PARK

By Dr. Claire Osmond

A. Introduction

1. My name is Dr Claire Osmond MBBS MRCP DRCOG MRCGP. I have been a GP partner and GP trainer in Chippenham for 20 years. I retired in December 2024. I have lived in Alderton for 25 years

2. The countryside surrounding Lime Down Solar Park is a beautiful and historic landscape, characterised by quiet lanes, agricultural land, and traditional stone-built villages. Lying on the edge of the Cotswolds National Landscape, it is a place cherished by walkers, cyclists and horse-riders who come for its tranquillity, open views, and deep connection to nature. As the Landscape and Visual Impact Report of Carly Tinkler observes, these are highly valued landscapes, which are highly susceptible to harm from industrial development.

3. As members of the public explained at the Open Floor Hearing, many people moved to the area surrounding Lime Down Solar Park because of the peace, the open countryside, and the everyday access to nature that this place offers. However, for many this is more than just a pleasant view – it is a way of life that supports physical health, mental wellbeing and a sense of balance that is increasingly rare in the modern world.

4. Health is a cross-cutting issue for the Examination and SLD will highlight how many of the Scheme's impacts directly intersect with it. The way individuals enjoy the landscape, take recreation, socialise, and maintain a healthy life is inseparable from the area in which they live. The loss of visual amenity, alongside non-visual effects such as noise and vibration, will undermine the mental health and wellbeing of local residents. In addition, any reduction in access to green spaces or diminished use of recreational routes, whether as a consequence of construction or their settings having been adversely affected, will limit opportunities for physical exercise and everyday engagement with nature. These are essential to sustaining good health.

5. I confirm that while I have prepared this paper on behalf of SLD, the opinions I express are my own, based on the information available to me and my professional expertise.

B. National and Local Policy

6. NPS EN-1 recognises that energy infrastructure has the potential to impact on the health and well-being of the population. Direct impacts on health include increased traffic, air or water pollution, dust, and noise. It recognises that it may also have indirect health impacts, for example, if the infrastructure affects access to key public services, transport, or the use of open space for recreation and physical activity (NPS EN-1, §4.4.3). As a consequence, applicants are required to assess the effects of each element of a project and identify any potential adverse health impacts and any measures to avoid, reduce, or compensate these impacts.

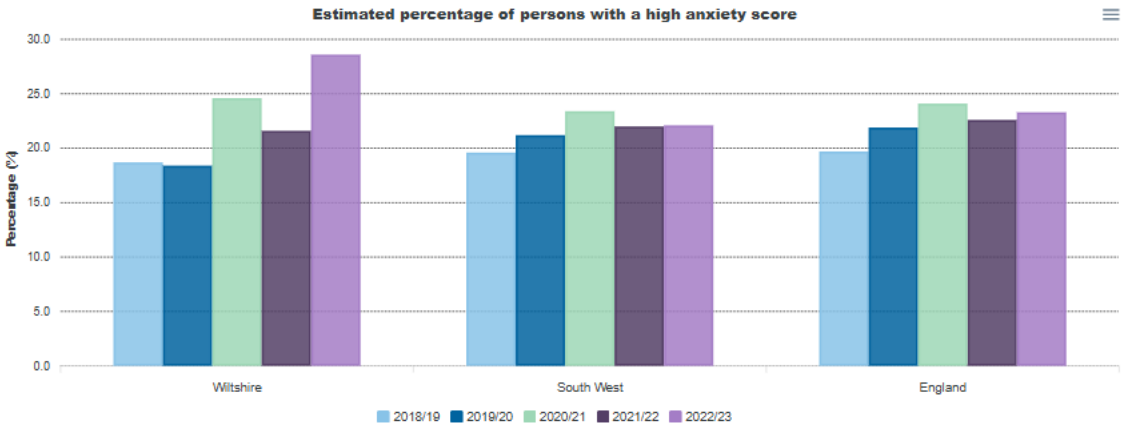
7. Paragraph 4.4.8 of EN-1 notes that where an area is not subject to separate regulation (as is the case for example, air pollution), the Secretary of State "*may want to take account of health concerns when setting requirements relating to a range of impacts, such as noise.*"

8. The most recent version of the NPPF (amended 2024 and February 2025) promotes the preservation of healthy and safe communities. While the NPPF does not contain specific policies for NSIPs, its policies are relevant and may be given weight in decision-making. Chapter 8 observes that "*access to a network of high quality open spaces and opportunities for sport and physical activity is important for the health and well-being of communities, and can deliver wider benefits for nature and support efforts to address climate change"* (§103). It further emphasizes the importance of proactively seeking to "*protect and enhance public rights of way and access, including taking opportunities to provide better facilities for users"* (§104).

Health in Wiltshire

9. The Wiltshire Joint Strategic Needs Assessment recognises mental and emotional health as a strategic priority for Wiltshire. The Wiltshire Joint Strategic Needs Assessment recorded that over a quarter of people (28.6%) of people aged 16 and over in Wiltshire reported elevated levels of anxiety. This was higher than estimates in both the South West (22.1%), as well as England (23.3%):[1]

[1] Wiltshire Joint Strategic Needs Assessment, 'Health and Disease' (Wiltshire Intelligence, 2025), available here.



Definition: The percentage of respondents aged 16+ years responding with a score of 6 to 10 to the question "Overall, how anxious did you feel yesterday?" in the ONS Annual Population Survey (APS). Responses are given on a scale of 0 to 10 where 0 is not anxious and 10 is the highest level of anxiety.

Data source and time period: Office for National Statistics (ONS), Annual Population Survey (APS), 2018/19 - 2022/23, via the OHID Fingertips tool.

10. The JSNA likewise records that 11.8% of adults registered with a GP in Wiltshire were recorded as having depression, although Wiltshire's prevalence was consistent with/ below trends in the South West and England. Connectedly, hospital admissions as a result of self-harm in 10-24 year olds in Wiltshire increased every year between 2016 amd 2020. In 2023/2024, the rate of hospital admissions was 215.2 per 100,000 of the population – comparatively higher than rates reported in the south west (174.9) and in England (117.0).[2]

11. The Wiltshire Joint Health and Wellbeing Strategy (2023-2032) recognises that good health is also about the environments in which the public of Wiltshire lives and works and the importance of focussing on the social and environmental factors impacting people's lives.[3]

C. Likely Impacts of Lime Down

Loss of Green Space

12. It is well known that the demand for mental health services is rising in England, particularly among children and young people.[4] Mental health services are vastly under-

[2] Wiltshire Joint Strategic Needs Assessment, 'Health and Disease' (Wiltshire Intelligence, 2025), available here.
[3] Wiltshire Joint Health and Wellbeing Strategy (Wiltshire Gov), available here.
[4] Website of the British Medical Association, 'Mental Health Pressures in England' <https://www.bma.org.uk/advice-and-support/nhs-delivery-and-workforce/pressures/mental-health-

resourced to meet growing demand, resulting in long waitlists and high thresholds for treatment.

13. There is a body of mental health research which has found that greenspace is associated with population-level reductions in anxiety, depression, mood disorders, and mental illness.[5] Greenspace can help alleviate poor mental health by offering avenues for mindfulness and stress reduction. In that context, and against a backdrop of the England's vastly under-resourced mental health services, greenspace has a vital role to play as a widely available and publicly accessible form of preventative mental health care. Within England, the NHS endorses "green social prescribing", the practice of supporting people to engage in nature-based interventions and activities to improve their mental and physical health.[6]

14. In 2025, research conducted at the Appalachian State University explored how greenspace may benefit mental health. The exploratory study leveraged publicly available greenspace data against health information within North Carolina. The study built on previous research which had identified that communities with the lowest quantities of greenspace had the highest prevalence of poor mental health outcomes Authors Ryan et al hypothesised "*place plays an essential role in the greenspace-mental health association among young people; such that neighbourhoods with higher quantities and better accessibility of greenspace will be associated with a lower prevalence of poor mental health outcomes.*"[7] After conducting the exploratory study, the authors observed in their discussion:

> "Our analysis found that higher greenspace quantity was associated with a lower prevalence of poor mental health outcomes (i.e., anxiety, depression, mood disorders, substance use disorders and mental and behavioral disorders) in urban and suburban neighborhoods, whereas better greenspace accessibility was associated with a lower prevalence of poor mental health outcomes in urban, micropolitan and rural/isolated areas. Poor mental health prevalence was lower in small towns and rural/isolated communities with higher greenspace quality (operationalized as the PAR). Our findings suggest that greenspace may be protective

pressures-data analysis#:~:text=Between%202017%20and%202022%2C%20rates,10%20to%201%20in%204> accessed 19 April 2026

[5] See, by way of example, those papers recorded in Ryan, S. C., Sugg, M. M., Runkle, J. D., & Thapa, B. (2024). Advancing understanding on greenspace and mental health in young people. *GeoHealth*, *8*, e2023GH000959.

[6] NHS England, 'Green social prescribing', discussed here.

[7] ibid.

of a wide suite of mental health outcomes among young people, and this association varies substantially with rurality. These results can help guide targeted, place-based greenspace interventions to lower the prevalence of poor mental health outcomes among young people…

[…]

Better greenspace accessibility was associated with a lower prevalence of poor mental health outcomes in urban, micropolitan, and rural/isolated neighborhoods. Our results corroborate past research, which found greenspace accessibility was significantly associated with lower mental health burdens among young people in urban communities (Markevych et al., 2017; Zach et al., 2016), and contribute new knowledge that this association is also present in micropolitan and rural communities…

[…]

In both small towns and rural and isolated areas, worse greenspace quality, when operationalized as the PAR, was associated with a higher prevalence of poor mental health outcomes."

15. Here, hundreds of hectares of greenspace would be lost as a consequence of the scheme. Equally, the Scheme is likely to have greater landscape impacts due to the use of 4.5m tracker panels (see the Landscape and Visual Impact Report of Carly Tinkler). As a consequence, the scheme is likely to have an adverse effect on the mental health of the public.

16. The Applicant might suggest that residents can find green spaces elsewhere however, because of the design of the project, several villages will be surrounded by solar panels. Likewise, there is cumulative effect of additional solar fields in the corridor of North Wiltshire.

<u>Loss of Community</u>

17. The scale and design of the Scheme would physically break up the visual connection between the villages and the community connection as well. During construction, the volume of heavy, industrial traffic on our narrow rural lanes will make travelling between communities difficult and potentially dangerous. Once built, the everyday routes that link our villages will become less pleasant and more challenging to use, bordered by extensive stretches of solar panels rather than open countryside. This change to the character and usability of local routes may contribute to increased isolation and loneliness, particularly for those who rely on these paths for social contact and daily movement.

18. The solar field also poses a significant risk to the mental health and wellbeing of residents. The stress associated with the loss of landscape, the industrialisation of familiar spaces, and the ongoing non-visual impacts of the Scheme could increase demand on already stretched local health services, including GP practices and secondary mental health support provided by the Avon and Wiltshire Mental Health Partnership (AWP). It is concerning that these services do not appear to have been meaningfully consulted, despite the foreseeable pressures. A community liaison funded by the developer would not be capable of absorbing or mitigating this level of impact on community mental health.

Public Rights of Way and Amenities

19. NPS EN-1 para. 5.11.30 recognises that '*Public Rights of way, National Trails, and other rights of access to land are important recreational facilities for example for walkers, cyclists and horse riders' (emphasis added). Applicants should 'take appropriate mitigation measures to address adverse effects' on people using these resources; 'consider what opportunities there may be to improve or create new access'; and if 'revising' existing rights of way, consider 'the use, character, attractiveness, and convenience of the right of way'*.

20. The LVIA Report of Carly Tinkler sets out detailed conclusions in respect of the impact on amenity by the Scheme. I do not repeat those conclusions here, but I note that she observes that impacts on the highest sensitivity amenity receptors would experience significant adverse effects for all phases of the Scheme (§9.2). She concludes that many popular rights of way would be adversely affected including long-distance trails, and the landscapes occupied by the sites form an important and integral part of the recreational experience (§9.42).That report likewise notes that effects on the health, well-being and quality of life of residents in their homes and gardens is an important consideration in planning and assessment and for those who use landscapes beyond their homes as a valuable resource for recreational and social amenity.

21. Loss of access to familiar walking and cycling routes will significantly reduce residents' ability to manage their mental health in the ways they normally would. National Health England's *Moving More – Living More* initiative emphasises the importance of adults

achieving at least 150 minutes of physical activity per week, with walking and cycling identified as key, accessible forms of exercise. Any degradation of PROW or the wider landscape setting will directly affect people's capacity to maintain these healthy routines. Reduced access to green spaces, diminished enjoyment of local routes, and the industrialisation of a previously tranquil environment all have well established impacts on mental health and wellbeing.

Noise

22. The complex relationship between noise and mental health remains an under-researched area.

23. There is a growing body of research into the impact of noise pollution on many aspects of human health. Primarily, this research has indicated that there is a link between environmental noise exposure to increases in blood pressure and cardiovascular ailments. Additionally, further research has indicated that exposure to noise can impact the central nervous system, increasing the susceptibility to mental health conditions such as depression, anxiety, and other behavioural issues.

24. A study published in 2022 showed significant pooled associations between high noise annoyance and general mental health problems, as well as diagnoses of depression and anxiety disorder, and general mental health.[8] The authors posit that noise exposure may induce the release of stress hormones:

> "The proposed biological mechanism underlying the noise annoyance and mental health relationship is that noise exposure may induce the release of stress hormones, disrupting hormonal rhythms via activation of the Hypothalamic–Pituitary–Adrenal (HPA) axis. Dysregulation of the HPA axis is significantly associated with a variety of mental health disorders, including depression, PTSD, etc., which leads to a hypothesised link between noise exposure and mental health problems in humans. Noise annoyance is a proxy for the dissatisfaction and distress associated with noise exposure, implying that noise annoyance may act as a mediator between noise exposure and health outcomes. This may explain why we found a strong relationship between noise annoyance and mental health, whereas other meta-analyses to date have discovered only limited evidence of the relationship between actual noise levels and mental health outcomes."

[8] Gong, X.; Fenech, B.; Blackmore, C.; Chen, Y.; Rodgers, G.; Gulliver, J.; Hansell, A.L. Association between Noise Annoyance and Mental Health Outcomes: A Systematic Review and Meta-Analysis. Int. J. Environ. Res. Public Health **2022**, 19, 2696. https://doi.org/10.3390/ijerph19052696

25. Their findings conclude that high noise annoyance is potentially an important mediator of the relationship between noise exposure and mental health outcomes.

26. The Noise Report, completed by Ian MacArthur on behalf of SLD observes that significant changes in noise level and character are anticipated by the Scheme. There are no practicable options for mitigation of external noise levels available to residential dwellings affected from noise from the development. For residents, mitigating noise would require keeping windows closed and finding other means of ventilation in the summer months. Likewise, significant impacts are expected on many PROWs.

D. Conclusion

27. The proposed Lime Down Solar Park would reduce access to nature, diminish the enjoyment of local routes, and disrupt the physical and visual connections between villages, increasing the risk of isolation and undermining community cohesion. Noise, vibration, heavy construction traffic, and the dominance of 4.5m panels would further erode residents' wellbeing. Given Wiltshire's already elevated levels of anxiety and the pressures on mental health services, the cumulative loss of greenspace, amenity, tranquillity, and recreational routes represents a significant and foreseeable health burden that the scheme does not adequately mitigate.

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Review

Association between Noise Annoyance and Mental Health Outcomes: A Systematic Review and Meta-Analysis

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Abstract: To date, most studies of noise and mental health have focused on noise exposure rather than noise annoyance. The purpose of this systematic review and meta-analysis was to evaluate whether the available evidence supports an adverse association between noise annoyance and mental health problems in people. We carried out a literature search of Web of Science, PubMed, Scopus, PsycINFO, and conference proceedings published between 2000 and 2022. Thirteen papers met the inclusion criteria. We conducted meta-analyses of noise annoyance in relation to depression, anxiety, and general mental health. In the meta-analyses, we found that depression was approximately 1.23 times greater in those who were highly noise-annoyed (N = 8 studies). We found an approximately 55% higher risk of anxiety (N = 6) in highly noise-annoyed people. For general mental health (N = 5), highly annoyed participants had an almost 119% increased risk of mental health problems as assessed by Short Form (SF) or General Household Questionnaires (GHQ), but with high heterogeneity and risk of publication bias. In conclusion, findings are suggestive of a potential link between noise annoyance and poorer mental health based on a small number of studies. More evidence is needed to confirm these findings.

Keywords: environmental and neighborhood noise; traffic noise; noise annoyance; mental health; depression; anxiety disorder; general mental health

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1. Introduction

Mental and addictive disorders were estimated to affect over 1 billion people worldwide in 2016, accounting for 7% of the global burden of disease as measured in disability-adjusted life year (DALYs) and 19% of all years lived with disability [1]. Mechanistic and epidemiological evidence suggests that exposure to traffic noise could be associated with poorer mental health in the population, either directly or via noise annoyance. Noise annoyance is a stress reaction to environmental noise [2], which is thought to be linked to the release of catecholamines from the hypothalamic–pituitary–adrenal axis [3]. Repeated noise annoyance may increase the risk of higher stress-hormone exposures [3], which could be associated with a variety of mental health disorders [4].

The link between noise exposure and mental health disorders is garnering increasing attention because noise pollution has long been a persistent urban problem in developed countries. Environmental Noise Guidelines for the European Region recommend reducing road and railway traffic noise levels to under 53 and 54 decibels (dB) Lden, respectively, as noise levels exceeding these thresholds have been linked to adverse health effects [5]. However, the European Commission estimated that 125 million people in Europe are

exposed to noise levels greater than 55 decibels Lden from road traffic, with over 37 million exposed to noise levels greater than 65 dB Lden [6]. England's third round of noise mapping, conducted in 2017, found that approximately 11.54 million and 1.50 million people living inside and outside agglomerations (major urban areas), respectively, were exposed to noise levels greater than 55 decibels Lden from roads and railways [7–9].

Systematic literature reviews to date have found statistically significant associations between aircraft noise exposure and depression in the general population, but not between noise from other sources and other mental health outcomes [2,10–13]. A number of studies, however, have reported statistically significant associations between noise *annoyance* and mental health outcomes for neighbourhood [14], road traffic [14], and aircraft noise [14,15]. The complex relationship between noise and mental health, including the mediating effect of noise annoyance, remains an under-researched area, but could provide mechanistic insight into the link between noise exposure and mental health issues [16].

The purpose of this systematic review and meta-analysis is to examine whether existing studies support a negative association between high noise annoyance and mental health outcomes in people. Highly annoyed participants are defined as individuals who in a questionnaire selected "very" or "extreme" on a 5-point verbal scale for annoyance (HA_V), the top three highest values on an 11-point numeric scale (HA_N), or the weighted top two verbal responses for the 5-point verbal question (HA_{VW}), as recommended by ISO/TS 15666:2021 [17].

The mental health outcomes of concern include depression and anxiety disorder, which affect approximately 4.4% and 3.6% of the global population, respectively [18]. We also investigated the relationship between high noise annoyance and general mental health.

2. Methods

This systematic review and meta-analysis aims to examine whether high noise annoyance can be associated with negative mental health outcomes. We conducted the study in accordance with PRISMA guidelines [19,20], and synthesised evidence using the PECCOS (population, exposure, comparator, confounder, outcome, and study design) procedures used for the systematic reviews underpinning the WHO 2018 Noise Guidelines for the European Region [5,21,22].

In our systematic review and meta-analysis, three reviewers (X.G., C.B., Y.C.) independently selected relevant papers identified through a comprehensive literature search and extracted data using a standardised proforma.

2.1. Paper Identification

We identified papers through searches of four databases, manual searches of relevant conference proceedings, referrals from colleagues, and review of papers identified in systematic reviews examining the mental health effects of noise exposure [2,11,12,23–25]. see Appendix A Table A1 shows the full list of conferences and search terms used to scan proceedings.

We (X.G., Y.C., B.C.) searched the Web of Science, PubMed, Scopus, and PsycINFO databases from 2000 to January 2022 for studies that examined the relationship between annoyance from any noise sources and the mental health outcomes of interest. See Appendix A Table A2 contains the search terms used in Web of Science, PubMed, Scopus, and PsycINFO.

The search results were imported into EndNote. After eliminating duplicates, XG, CB, and YC independently screened the remaining studies using the PECCOS inclusion and exclusion criteria listed in Table 1 [5]. Since the purpose of our research is to quantify the relationship between high noise annoyance and mental health in people, we excluded any papers that could not be included in a quantitative meta-analysis. Disagreements were resolved through discussion.

Table 1. PECCOS review inclusion and exclusion criteria.

Category	Inclusion	Exclusion
Population	We considered studies that examined the • general adult population, or • a subgroup of the general adult population, such as men or women.	
Exposure	We restricted noise sources to environmental or neighbourhood noise from road, rail, aircraft, commercial, industrial, wind turbine, and construction activities. To assess noise annoyance, questionnaires were limited to • standard annoyance questionnaires (5-point verbal question or 11-point numeric question) or • questionnaires that mentioned noise disturbance or bothering.	We excluded studies examining occupational noise exposure or noise perception.
Confounders	No inclusion confounder criteria were used, following methods used for the systematic reviews underpinning the 2018 WHO Noise Guidelines for the European Region [5].	
Outcomes	We considered studies that assessed mental health outcomes using objective or self-reported measures, such as diagnosis of disease or prescription of drugs. We also included studies that implemented mental health screening tools but dichotomised the outcomes as cases or non-cases.	We excluded studies that used mental health screening tools but did not dichotomise the outcomes.
Study types	• Cross-sectional • Longitudinal, • Prospective and retrospective cohort, • Case-control, and • Experimental studies with quantitative results.	

2.2. Definition of Outcomes

We primarily focused on anxiety and depressive disorders. However, a significant proportion of published research examines people's overall mental health, which may be associated with but not classified as depression or anxiety disorders. We therefore also looked at general mental health as a third outcome category.

Most relevant studies on depression and/or anxiety disorders relied on either self-reported disease diagnoses (SRD) or self-reported use of psychotropic medications (SRM), such as antidepressants and anxiolytics. In one study, validated questionnaires (VQ) such as the Patient Health Questionnaire-9 (PHQ-9; for depression) and the Generalized Anxiety Disorder-2 (GAD-7; for anxiety disorder) were used to detect cases of depression or anxiety disorders by comparing participant scores to cut-off values. One study identified cases using all three of the methods outlined above: SRD, SRM, and VQ. Another study screened for depressive and/or anxiety symptoms using unvalidated questionnaires (UQ).

Relevant publications on general mental health used a variety of instruments that can be classified into two broad categories. The first group comprises two versions of the General Health Questionnaire: GHQ-12 and GHQ-30. We refer to GHQ-12 and GHQ-30 collectively as GHQ studies. The second includes the Short Form Survey; there are multiple versions of Short Form surveys commonly used in relevant studies. They include SF-36 (and its derivative MIH-5) and SF-12 (a shorter version of SF-36). We refer to SF-12, SF-36, and MIH-5 collectively as SF studies. These screening tools for general mental health have varying scales, but we included only studies that used cut-off values to dichotomise outcomes as cases or non-cases.

We did not consider perceived stress levels as there was only one study that examined this outcome using the Perceived Stress Scale (PSS).

All of the outcomes are binary, which allows for statistical comparisons of the estimates.

2.3. Definition of Exposure

We restricted our analysis to annoyance caused by any sources of environmental and neighbourhood noise.

The 11-point numeric noise-annoyance scale (range 0–10; a higher number indicates a greater degree of annoyance) and the verbal 5-point response scale (1 "Not at all", 2 "Slightly", 3 "Moderately", 4 "Very", and 5 "Extremely") are two frequently used questionnaires for identifying noise annoyance.

We adopted three definitions of high noise annoyance in accordance with ISO/TS 15666:2021 [17]. The first is HA_N, which uses the top 3 points (8, 9, and 10) of the 11-point numeric noise-annoyance scale to identify highly annoyed participants [2,17,26]. HA_V uses the upper two steps (4 "Very" and 5 "Extremely") of the verbal 5-point response scale to define highly annoyed individuals [2,17,26–28].

Because the HA_V method's cut-off value of 60% is lower than the 72% employed in research using the HA_N approach [28], a third definition, HA_{VW}, was proposed, which uses the same 5-point verbal scale but weights "Very" by 0.4 and "Extremely" in full to produce a mathematical similarity between the former two approaches [17].

HA_{VW} has a mathematical cut-off value that is similar to HA_N. Although HA_V has a lower cut-off threshold than HA_N, the verbal questions may be interpreted differently from the numerical questions [17]. They both detect levels of annoyance that are not considered trivial or moderate [28].

Most relevant studies used either HA_V or HA_N to identify highly annoyed participants, but none used HA_{VW}.

Additionally, there were studies that used 5- or 11-point scales but only made mention of being "disturbed" or "bothered" by noise on the questionnaires. We treated these questionnaires comparable to standard ones, considering being disturbed or bothered as elements of annoyance [2]. This allowed us to include two additional studies into the meta-analysis.

To increase the number of studies included in the meta-analyses, we also included studies that employed a three-point scale. We chose the highest score as indicative of high annoyance.

We considered perception of noise to be fundamentally different from the three components of noise annoyance as defined by Guski [2] (disturbance, emotional and cognitive response). Therefore, we excluded publications that used noise perception as the exposure variable.

HA_N, HA_V, as well as other variables of high annoyance are binary, with one value indicating highly annoyed and the other otherwise.

2.4. Effect Size Extraction

We combined all of the studies for each outcome, regardless of the source of the noise, on the assumption that the annoyance was having the same biological effect on people.

We used odds ratios as the unified effect size, because all studies but one used logistic regressions to analyse data and reported odds ratio. Eze [29] reported relative risk. We converted the relative risk and 95% CI into odds ratio by using the formula $OR \approx RR^2$, assuming that mental health is a common health problem among participants (reported by >15% participants) [30].

We extracted estimates whenever possible from models in which noise annoyance as the only noise exposure variable. Two studies [15,31] (both focused on general mental health) presented results from models that incorporated both noise levels and noise annoyance, with noise annoyance potentially serving as both an exposure and a mediator. Given the low number of studies available in total, we also included these in meta-analysis; sensitivity analyses excluding these papers did not lead to effective changes in results or interpretation.

We derived the estimates from the fully adjusted model for each paper. If there were multiple estimates from the fully adjusted specification, the most conservative (lowest in size) coefficients were then extracted. For instance, Schreckenberg [31] provided two estimates of the relationship between noise annoyance and general mental health, based on the SF-12 and SF-36 mental health scales, respectively [31], and we selected the SF-12

estimate. Eze [29] reported findings using both a full sample and a sample of non-movers, the latter of which was used.

2.5. Risk of Bias

Bias risk was assessed using the checklist in see Appendix A Table A3 of the Methodology for Systematic Evidence Reviews for WHO Environmental Noise Guidelines for the European Region [19]. The checklist contains five domains and a total risk of bias. For each study, the total risk is considered low when at least 4/5 domains are judged to be of low risk of bias, including domains 1, 2, and 3. Any study that does not meet this criterion is deemed high risk. Please see the Methodology document [19] for full details.

We created figures to summarise the risk of bias using the R package *robvis* [32].

2.6. Statistical Analysis

We estimated pooled odds ratio and 95% confidence intervals (CI) using random-effects meta-analysis. The random-effects meta-analysis relies on an assumption that the exposure effect from each individual study might be different [33,34], which enables the regression to incorporate sources of heterogeneity [33]. The analysis was carried out using the *metan* package [35] in Stata 17 [36]. We log-scaled odds ratios and 95% confidence intervals to make data nearly symmetrical for the meta-analysis. We reported exponentiated pooled effects and 95% CI.

We examined the pooled association between annoyance caused by any types of noise and mental health problems. Due to insufficient studies, we were unable to analyse the relationships relating to noise annoyance from specific sources, e.g., traffic or neighbourhood.

We hypothesised that pooled analyses of depression or generalised anxiety disorder determined by either self-reported diagnosis or questionnaire (SRD/VQ/UQ) or self-reported medication (SRM) may exhibit high heterogeneity due to studies detecting varying degrees of severity. Studies that used SRD/VQ/UQ to screen for depression and anxiety disorder may identify patients with a broader spectrum of severity. By contrast, individuals suffering from moderate-to-severe mental health problems were likely to be included in studies that used SRM to identify cases. Thus, we conducted subgroup analyses by dividing studies into SRD/VQ/UQ and SRM. The study that identified cases using SRD, VQ, and SRM was assigned to the SRM subgroup.

Moreover, studies on general mental health used two broad categories of validated instruments: the GHQ and the SF. These two instrument families appear to assess different aspects of mental health [37], that may introduce heterogeneity into the meta-analysis. We thus performed meta-analysis on subgroups and divided samples into GHQ and SF.

To assess the effect of outliers on our findings, we used leave-one-out analysis to recalculate the pooled effects multiple times by omitting one study from each analysis.

To assess publication bias, funnel plots were used. Each plot depicted the effect size of each study on the X axis and the standard error on the Y axis.

2.7. Quality of Evidence

The overall quality of evidence was judged according to the adapted version of the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) guidelines, as used in systematic reviews of noise and health conducted to develop the 2018 WHO Noise Guidelines for the European Region [22,38].

3. Results

We found 350 articles in Web of Science, PubMed, Scopus, and PsycINFO database searches. One additional record was identified through reviewing conference proceedings and literature reviews. We removed 105 duplicates and additional 190 articles that did not meet the inclusion criteria after screening titles and abstracts. Following a full-text analysis, we eliminated 42 papers for the reasons listed in Figure 1. This left us with 13 papers for review (listed in Table A4). The full description of studies is presented in Table A6.

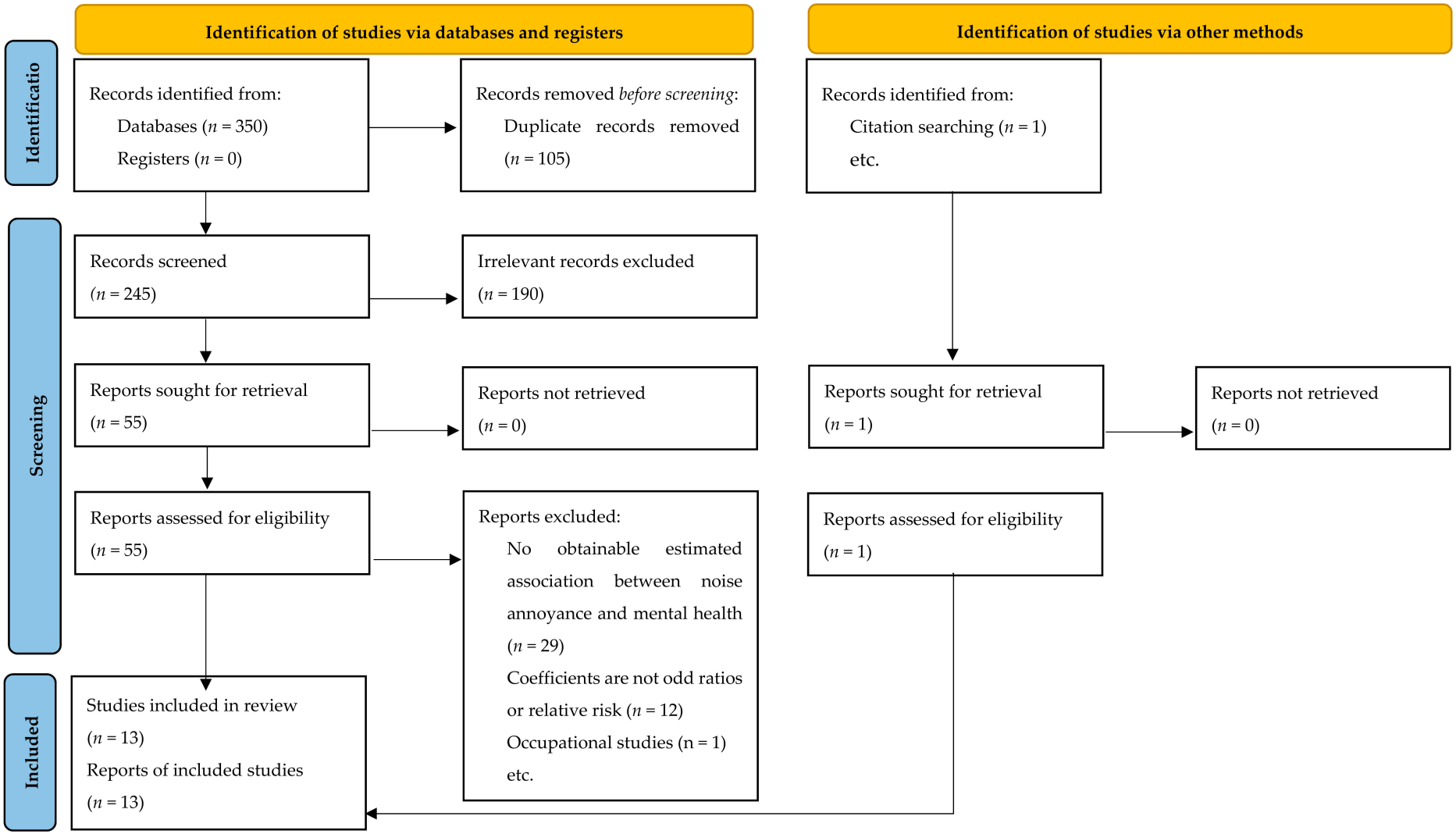

Figure 1. PRISMA flow chart showing number of papers identified [20].

The average number of participants was around 7427 (range 1244 to 19,294). The participants were selected from the general population (N = 6), the male population (N = 1), the general population living near airports (N = 4), and the general population living in multistorey houses (N = 2). All studies were conducted in European countries. Except for two longitudinal studies [39,40], the studies were all cross-sectional.

One study assessed noise annoyance using both 5-point and 11-point scales. Others used either 3-point (N = 2), 5-point (N = 7), or 11-point (N = 3) scales. Two studies used HA_N while two used HA_V to define high annoyance. The remaining studies did not use standard definitions of high annoyance as suggested by Clark [17]. The sources of noise annoyance included aircraft (N = 8), road vehicles (N = 6), trains (N = 3), neighbourhood (N = 6), industrial (N = 2), and unspecific traffic sources (N = 1).

Seven studies examined both depression and anxiety disorders [40–45], while two focused exclusively on depression [29,46]. Measures used in these studies included the intake of antidepressants (N = 4) and anxiolytics (N = 3), as well as self-reported physician diagnosis of depression (N = 2). Beutel [40] and Beutel [43] used PHQ-9 and GAD-2 to screen for depression and anxiety disorder. Jensen [47] used unvalidated questionnaires to identify the case of depression and anxiety.

Five papers used self-reported mental health measures. Baudin [15] used GHQ-12 and defined cases as those with a score ≥ 3 on the scale. Stansfeld [48] adopted a threshold of 4 on GHQ-30. Schreckenberg [31] and Jensen [41] used the SF-12, and the cut-off values in these two studies were median and 52 on the scale, respectively. MHI-5 was used by Hammersen [14] with a cut-off value of 52.

3.1. Risk of Bias

Figures A1 and A2 illustrate the detailed evaluations of each paper against each criterion. More than three-quarters of studies had a high risk of bias. Two primary reasons for this were domain 1—a lack of standardised definitions of high noise annoyance being used (8 studies); and domain 3—a study response rate below 60% (N = 3). An additional reason for high bias risk ratings was blinding (N = 3). Finally, using unvalidated mental health questionnaires contributed to a high risk of bias score for three studies.

3.2. Meta-Analysis Results

3.2.1. Depression

There were eight studies available, of which six were included in the meta-analysis, as two studies used the same dataset; we selected Baudin [45] (using data from HYENA and DEBATs studies) over Floud [44] (using data from HYENA only) and Beutel [40] (using data from Gutenberg Health Study—longitudinal design) over Beutel [43] (using data from Gutenberg Health Study—cross-sectional design).

As illustrated in Figure 2, the pooled odds ratio for the forest plot for all six studies was 1.23 (95% CI [1.03, 1.48]). However, I^2 and Q were 60.4% and 12.63, respectively, implying significant heterogeneity between studies.

One potential source for the high degree of heterogeneity was the difference in the way in which measurement of depression was made. The pooled coefficient for three studies that used SRD or VQ was 1.50 (95% CI [1.03, 2.19]) and significant. Although I^2 and Q remain high in SRD or VQ studies, subgrouping significantly reduces the heterogeneity between studies that used SRM as the outcome. The effect for this subgroup was 1.08 (95% CI [1.01, 1.16]), which was statistically significant and with low I^2 and Q.

A leave-one-out analysis (see Appendix B Figure A3) indicates that Jensen [47] was probably an outlier, likely owing in part to the study's use of an unvalidated questionnaire to detect depression and anxiety.

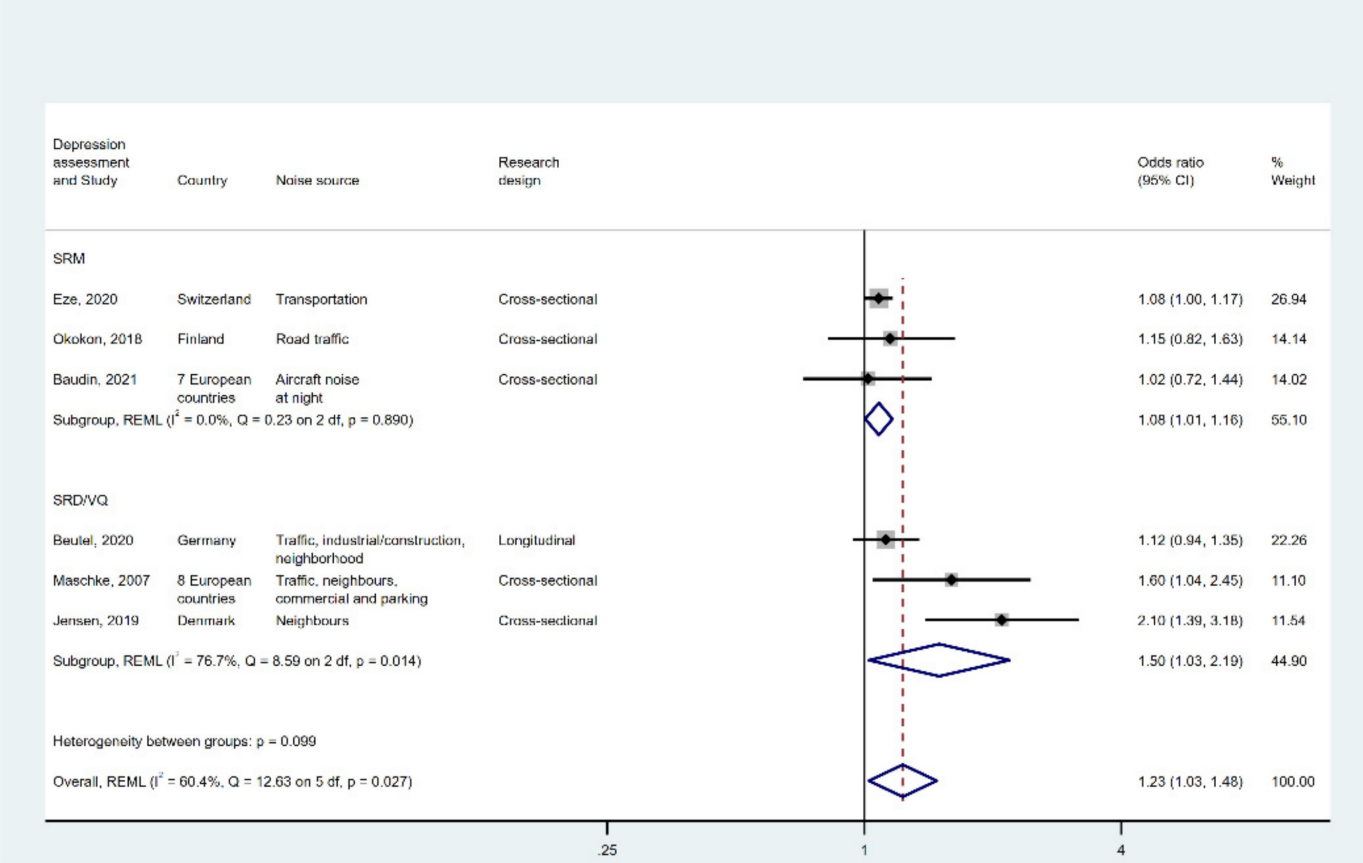

Figure 2. Forest plot displaying the link between high noise annoyance and depression. Note: weights and between-subgroup heterogeneity text are from random-effects model.

3.2.2. Anxiety Disorder

We pooled data from four out of six relevant studies to assess the association between high noise annoyance and anxiety disorder. Again, we selected Baudin [45] (using data from HYENA and DEBATs studies) over Floud [44] (using data from HYENA only) for the same reason as stated previously, and Beutel [40] (using data from Gutenberg Health Study; longitudinal design) over Beutel [43] (using data from Gutenberg Health Study; cross-sectional design).

The forest plot in Figure 3 indicates that the pooled effect based on all four studies was 1.55 (95% CI [1.14, 2.10]), with large I^2 and Q, suggesting significant heterogeneity between studies.

When samples were divided into two subgroups based on outcome assessment methods (VQ/UQ vs. SRM), we again observed small I^2 and Q for the studies that used SRM to measure anxiety disorder. The odds ratio for the SRM subgroup was 1.44 (95% CI [1.15, 1.81]). Across studies that used VQ/UQ to detect anxiety disorder, the pooled association was much greater in size (OR = 1.73 95% CI [0.82, 3.66]), albeit non-significant. This subgroup has significant heterogeneity as suggested by the large I^2 and Q.

Figure A4 depicts the results of a leave-one-out analysis, which again suggests Jensen [47] was probably an outlier.

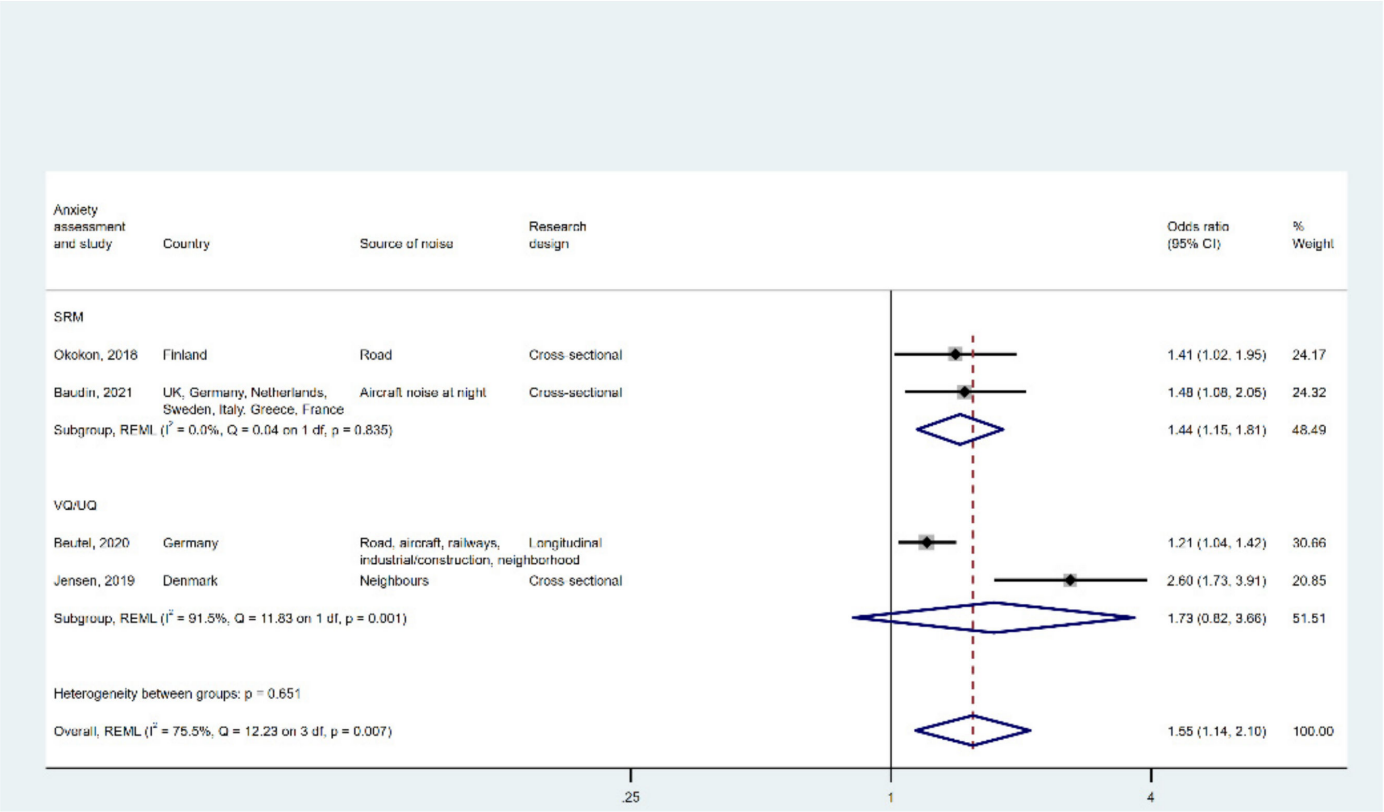

Figure 3. Forest plot displaying the link between high noise annoyance and anxiety disorder. Note: weights and between-subgroup heterogeneity text are from random-effects model.

3.2.3. General Mental Health

Six estimates were available from five studies (one study reported results separately for men and women), all of which used validated instruments to assess mental health that fall into two categories: GHQ and SF.

In Figure 4, the pooled effect is 2.19 (95% CI [1.49, 3.23]). However, I^2 is 94.10% and Q is 85.06, indicating a high degree of heterogeneity across studies. Subgroup analysis results show that a high level of noise annoyance was associated with an almost threefold increased risk of self-reporting a mental health problem (OR = 3.17, 95% CI [1.69, 5.95]), based on two studies that used either GHQ-30 or GHQ-12. The pooled odds ratio for the three SF studies was 2.00 (95% CI [1.27, 3.15]). According to their I^2 and Q, there appears to be significantly more heterogeneity across SF studies than across GHQ studies as judged by I^2 and Q.

We conducted a leave-one-out analysis, as shown in Figure A5, and identified Schreckenberg [31] using the SF-12 as a potential outlier.

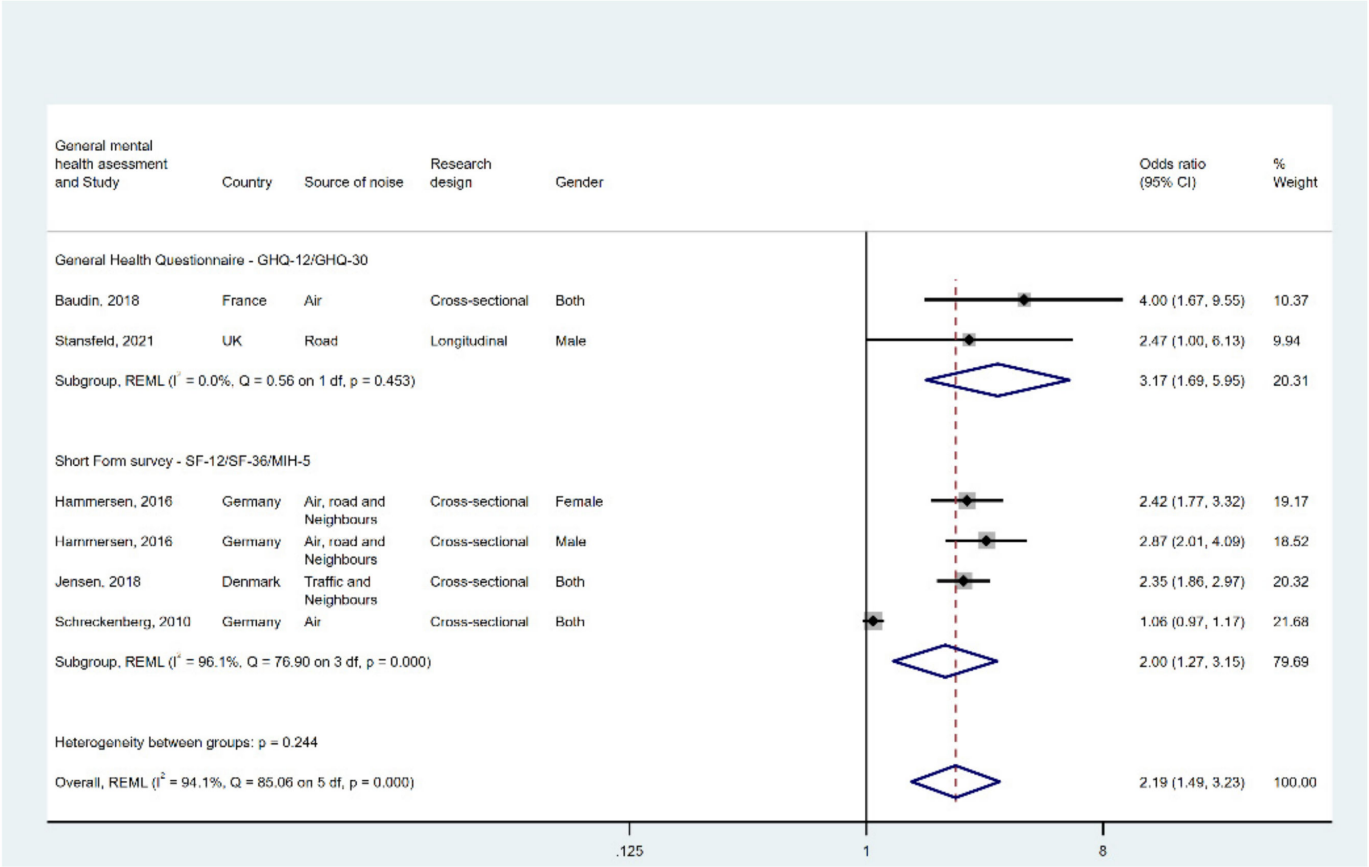

Figure 4. Forest plot displaying the link between high noise annoyance and general mental health. Note: weights and between-subgroup heterogeneity text are from random-effects model.

3.3. Publication Bias

Funnel plots in Figure A6 (depression studies) and Figure A7 (anxiety studies) illustrate a relatively symmetric funnel shape between studies that use SRM to identify cases. However, funnel plots for other subgroups of depression and anxiety studies, as well as for general mental health (Figures A6–A8) indicated an asymmetric shape, suggesting a high risk of publication bias.

3.4. Quality of Evidence

The quality of evidence using the GRADE system is presented in Table A5. We chose to separately assess each subgroup for depression and anxiety disorder included in the meta-analysis due to the significant heterogeneity within each domain. All subgroups and general mental health began with "low" ratings, which was consistent with the cross-sectional design used in all, but two studies. We rated evidence as 'very low' quality for all depression and anxiety subgroups, as well as the general mental health group.

4. Discussion

We conducted a meta-analysis of high annoyance from environmental and neighbourhood noise and three domains of mental health problems: depression, generalised anxiety disorder, and general mental health.

Our results (N = 13) show significant pooled associations between high noise annoyance and all three domains, albeit with a high degree of heterogeneity.

In subgroup analyses, we divided relevant studies according to health outcome identification (self-reported diagnosed (SRD) or validated questionnaire (VQ) or unvalidated questionnaire (UQ) detected vs. self-reported medication intake (SRM)) for each domain of mental health problem. We found a statistically significant correlation between high

noise annoyance and psychotropic medication use (antidepressant or anxiolytic) with a significantly low level of heterogeneity.

The coefficient size for anxiolytics was consistently larger than that for antidepressants, based on a small number of studies. Notably, a recent study that focused on actual noise levels rather than noise annoyance discovered a significant correlation between road noise levels and prescriptions for anxiolytics, but not for antidepressants [44]. Anxiolytics can be prescribed for sleep problems [44], which may contribute to a relationship between noise/noise annoyance and anxiolytics intake. Evidence to date, however, found a non-significant link between noise level and the prescription of hypnotics [44,48]. More detailed studies are needed to determine whether noise annoyance is related to moderate- to-severe anxiety or whether it is associated with sleep disturbance.

We combined all estimates of high noise annoyance regardless of the source of the noise. SRM-based studies on depression and anxiety disorders and GHQ-based studies on general mental health evidenced a low level of heterogeneity across studies. This supports our previous hypothesis that annoyance from environmental and neighbourhood noise may have the same biological effect irrespective of its source.

The proposed biological mechanism underlying the noise annoyance and mental health relationship is that noise exposure may induce the release of stress hormones [3,49], disrupting hormonal rhythms via activation of the Hypothalamic–Pituitary–Adrenal (HPA) axis [49]. Dysregulation of the HPA axis is significantly associated with a variety of mental health disorders, including depression, PTSD, etc. [4,50], which leads to a hypothesised link between noise exposure and mental health problems in humans. Noise annoyance is a proxy for the dissatisfaction and distress associated with noise exposure [51], implying that noise annoyance may act as a mediator between noise exposure and health outcomes [52–54]. This may explain why we found a strong relationship between noise annoyance and mental health, whereas other meta-analyses to date have discovered only limited evidence of the relationship between actual noise levels and mental health outcomes. A 2019 meta-analysis by Dzhambov [25] found a positive—albeit non-significant—correlation between road traffic noise levels and depression or anxiety disorder. A meta-analysis by Hegewald [12] published in 2020 also identified a non-significant increase in depression risk associated with a 10 dB increase in railway or road traffic noise, but a statistically significant higher risk of depression associated with the same increase in aircraft noise. There was an insufficient number of studies to meta-analyse the pooled relationship between noise exposure from aircraft and general anxiety disorder, as noted by Hegewald [12] and Dzhambov [25].

One issue in the interpretation of an association between noise annoyance and mental health is reverse causality. A competing theory argues that mental health may be a context factor that increases vulnerability to environmental stressors, and that noise annoyance, as a psychological response to stress, may be a result of poor mental wellbeing [55]. Evidence on causal directions is still very limited. One study used structural equation modelling (SEM) to investigate the causal direction of the relationship between aircraft sound exposure, aircraft noise annoyance, and mental-health-related quality of life (HQoL) [52]. Both annoyance and mental HQoL measured at survey wave one had an impact on mental HQoL and annoyance measured at survey wave two, suggesting that annoyance and mental HQoL are reciprocally associated with each other. The mediation effect of aircraft noise annoyance was found to be considerably higher than the mediation effect of mental HQoL, indicating that the effect of mental HQoL on annoyance is independent from sound exposure. In two of the three SEM models investigated, the direct effect of aircraft sound exposure on mental HQoL was not significant; that is, annoyance fully mediated the relationship between aircraft noise exposure and mental HQoL [52].

We cannot rule out either explanation based on the small number of studies and their cross-sectional nature. Further research is urgently needed to investigate the causal relationship between noise annoyance and mental health in people.

We focused on high annoyance from noise as the exposure because it is generally well defined and examined [2,17,26,28]. Being disturbed, bothered, and annoyed are common

feelings to daily nuisances. By concentrating on individuals who exhibited a high level of annoyance due to noise exposure, we are more likely to disentangle chronic stress responses from shorter-term negative experiences [26,27]. Furthermore, it is generally accepted that high annoyance is more likely to have clinical significance [56].

A strength of our study is that to the best of our knowledge, this systematic review and meta-analysis is the first to consider associations between noise annoyance (rather than noise levels) and mental health. We identified some possible sources of heterogeneity and conducted subgroup analysis. This contributed to a reduction in the degree of heterogeneity across some subgroups. Further research should also investigate potential differences between men and women in associations between high noise annoyance and depression and anxiety.

Limitations to our study include the fact that most studies used in our meta-analysis and systematic review were cross-sectional, limiting the ability to establish causality in the association between mental health and high noise annoyance. We identified that only a small number of studies are available, with some heterogeneity in both the exposure assessment and outcome assessment, and the grading of evidence as low-quality. We were unable to consider participant age ranges in the meta-analysis. A final limitation is that we used a non-mesh search strategy, which may introduce errors that could compromise the quality and validity of our systematic review [57].

Our findings, combined with limited evidence from longitudinal analyses of epidemiological data, suggest that high noise annoyance is potentially an important mediator of the relationship between noise exposure and mental health outcomes. This is of concern if noise annoyance has increased in recent years, as suggested by some studies [2,53,58]. Interventions to reduce the burden of ill health attributable to environmental and neighbourhood noise should focus on both noise exposure and noise annoyance.

5. Conclusions

To the best of our knowledge, this systematic review and meta-analysis is the first to consider associations between noise annoyance (rather than noise levels) and mental health. Our results suggest a negative link between high noise annoyance and depression, generalised anxiety disorder, and general mental health, based on a small number of studies. This finding supports the hypothesis that noise annoyance may be negatively associated with mental health problems in individuals. More studies are needed to investigate this further, but these tentative associations may suggest that public health interventions should focus on reducing noise annoyance as well as noise exposure.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of conference proceedings.

Conference	Search Terms Used	Link
Internoise 2000 to 2020 (held annually)	'mental health' and 'annoyance'.	https://www.ingentaconnect.com/content/ince/incecp#:~:text=The%20INTER%2DNOISE%20and%20NOISE,at%20the%20congress%20or%20conference (accessed on 23 June 2021)
International Commission on Biological Effects of Noise (ICBEN) 2000 to 2021 (held every 3 years)	'mental health' and 'annoyance'.	http://www.icben.org/Proceedings.html (accessed on 23 June 2021)
International Congresses on Acoustics (ICA) 2001–2019 (held every 3 years)	'mental health' and 'annoyance'.	https://www.icacommission.org/proceedg.html (accessed on 23 June 2021)
International Institute of Acoustics and Vibration (IIAV) 2005–2021 (held annually)	'mental health' and 'annoyance'.	http://www.proceedings.com/6995.html (accessed on 23 June 2021)

Table A2. Search terms used in Web of Science and PubMed database searches.

Database	Terms	Period Filter
Web of science	TS = ((“annoyance” OR “noise annoyance”) AND (“aircraft noise” OR “airport noise” OR “construction noise” OR “environmental noise” OR “hospital noise” OR “residential noise” OR “metro noise” OR “neighbourhood noise” OR “railway noise” OR “road traffic noise” OR “school noise” OR “traffic noise” OR “train noise” OR “transportation noise” OR “truck noise” OR “wind farm noise” OR “wind turbine noise” OR “wind turbine sound”) AND (“perceived well-being” OR “quality of life” OR “depression” OR “anxiety” OR “mental health” OR “mental well-being” OR “anxiety” OR “psychological symptom” OR “emotional disorder” OR “cortisol”))	3 January 2000–2022
PubMed	(“annoyance” OR “noise annoyance”) AND (“aircraft noise” OR “airport noise” OR “construction noise” OR “environmental noise” OR “hospital noise” OR “residential noise” OR “metro noise” OR “neighbourhood noise” OR “railway noise” OR “road traffic noise” OR “school noise” OR “traffic noise” OR “train noise” OR “transportation noise” OR “truck noise” OR “wind farm noise” OR “wind turbine noise” OR “wind turbine sound”) AND (“perceived well-being” OR “quality of life” OR “depression” OR “anxiety” OR “mental health” OR “mental well-being” OR “anxiety” OR “psychological symptom” OR “emotional disorder” OR “cortisol”)	4 January 2000–2022
Scopus	KEY ((“annoyance” Or “noise annoyance”) AND (“air-craft noise” OR “airport noise” OR “construction noise” OR “environmental noise” OR “hospital noise” OR “residential noise” OR “metro noise” OR “neighbourhood noise” OR “railway noise” OR “road traffic noise” OR “school noise” OR “traffic noise” OR “train noise” OR “transportation noise” OR “truck noise” OR “wind farm noise” OR “wind turbine noise” OR “wind turbine sound”) AND (“perceived well-being” OR “quality of life” OR “depression” OR “anxiety” OR “mental health” OR “mental well-being” OR “anxiety” OR “psycho-logical symptom” OR “emotional disorder” OR “cortisol”)) AND PUBYEAR AFT 2000	3 January 2000–2022
PsycINFO	(“annoyance” OR “noise annoyance”) AND (“aircraft noise” OR “airport noise” OR “construction noise” OR “environmental noise” OR “hospital noise” OR “residential noise” OR “metro noise” OR “neighbourhood noise” OR “railway noise” OR “road traffic noise” OR “school noise” OR “traffic noise” OR “train noise” OR “transportation noise” OR “truck noise” OR “wind farm noise” OR “wind turbine noise” OR “wind turbine sound”) AND (“perceived well-being” OR “quality of life” OR “depression” OR “anxiety” OR “mental health” OR “mental well-being” OR “anxiety” OR “psychological symptom” OR “emotional disorder” OR “cortisol”)	3 January 2000–2022

Table A3. Risk of bias assessment used for the systematic reviews underpinning the WHO Noise Guidelines for the European Region [22].

Domain	Judgement of Risk of Bias
Noise annoyance assessment leading to information bias	Low: Papers that defined highly annoyed participants using the top 3 points (8, 9 and 10) of the 11-point numeric noise annoyance scale (HA_N) OR the upper two steps ("Very" and "Extremely") of the verbal 5-point response scale (HA_V) OR the same 5-point verbal scale but weights "Very" by 0.4 and "Extremely" in full (HA_{VN}) High: Studies that did not define high noise annoyance OR High annoyance was defined in an approach that is different from Schultz and ICBEN definitions.
Bias due to confounding	Low: Papers that defined highly annoyed participants using the top three points on an 11-point scale OR upper 2 points in the 5-point scale. High: Studies that did not define high noise annoyance OR High annoyance was defined in an approach that is different from Schultz and ICBEN definitions.
Bias due to selection of participants	Low: The participants were drawn from an administrative dataset that contains data on the entire population. OR Randomly selected from the general population AND the response rate exceeded 60%. High: Participants selected from a non-probability sampling method OR The sample size is very small ($\leq$200) OR The response rate is lower than 60%.
Health outcome assessment leading to information bias i	Depression, anxiety disorder, and general mental health were the three primary domains. Mental health problems were quantified using clinically diagnosed psychiatric disorders, psychotropic medication use, and self-reported mental health instruments such as the PHQ-9 (depression), GAD 2 (anxiety), SF-12/36/MIH-5 (general mental well-being), and GHQ 12/30 (general mental health). Low: Studies had (i) clearly demonstrated classification of the mental disease if used self-reported diagnosis, OR (ii) clearly demonstrated substance prescribed if used medication intake, OR (iii) used validated mental health screening tool and cut-off values if screening instruments were used. High: Studies that used a non-validated questionnaire OR Studies that used a non-validated cut-off to dichotomise outcome.
Heath outcome assessment leading to information bias ii	We considered the bias to be Low If the data were from generic health study OR Pollution-themed studies that do not directly suggests noise is the main interest. OR The primary objective of these studies was to determine the association between noise pollution and health, but the blinding process was maintained.

Table A4. List of studies included in the analyses.

Study	Title	Country
Baudin, 2018 [15]	Aircraft noise and psychological ill-health: the results of a cross-sectional study in France	France
Baudin, 2021 [45]	The role of aircraft noise annoyance and noise sensitivity in the association between aircraft noise levels and medication use: results of a pooled analysis from seven European countries	UK, Germany, Netherlands, Sweden, Italy, Greece, France
Beutel, 2016 [43]	Noise annoyance is associated with depression and anxiety in the general population-the contribution of aircraft noise	Germany
Beutel, 2020 [40]	Noise annoyance predicts symptoms of depression, anxiety, and sleep disturbance 5 years later. Findings from the Gutenberg Health Study	Germany
Eze, 2020 [29]	Incidence of depression in relation to transportation noise exposure and noise annoyance in the SAPALDIA study	Switzerland
Floud, 2011 [44]	Medication use in relation to noise from aircraft and road traffic in six European countries: results of the HYENA study	UK, Germany, Netherland, Sweden, Italy, Greece
Hammersen, 2016 [14]	Environmental noise annoyance and mental health in adults: findings from the cross-sectional German health update (GEDA) study 2012	Germany
Jensen, 2018 [41]	Neighbour and traffic noise annoyance: a nationwide study of associated mental health and perceived stress	Denmark
Jensen, 2019 [47]	Neighbour noise annoyance is associated with various mental and physical health symptoms: results from a nationwide study among individuals living in multi-storey housing	Denmark
Maschke, 2007 [46]	Health effects of annoyance induced by neighbour noise	France, Germany, Slovakia, Hungary, Portugal, Italy, Switzerland, Latvia
Okokon, 2018 [42]	Traffic noise, noise annoyance and psychotropic medication use	FInland
Schreckenberg, 2010 [31]	Aircraft noise and quality of life around Frankfurt airport	Germany
Stansfeld, 2021 [39]	Road traffic noise, noise sensitivity, noise annoyance, psychological and physical health, and mortality	UK

Table A5. Quality of evidence [22].

	Depression		Anxiety Disorder		General Mental Health
	SRM	SRD/VQ	SRM	VQ/UQ	
Starting rating	Low	Low	Low	Low	Low
Risk of bias	Serious (2/3 high risk)	Moderate (1/4 high risk)	Serious (3/3 high risk)	Moderate (1/3 high risk)	Moderate (2/5 high risk)
Inconsistency	Low	Serious	Low	Serious	Serious
Indirectness	None	None	None	None	None
Imprecision	None	None	None	None	None
Publication bias	None	Serious	None	Serious	Serious
Strength of association	Small	Small	Small	Small	Large
Exposure-response gradient	None	None	None	None	None
Possible confounding	No serious bias	No serious bias	No serious bias	No serious bias	No serious bias
Overall	Very low	Very Low	Very low	Very Low	Very low

Note: The overall rating was rated on a scale of very low, low, moderate, and high. SRM = self-reported use of psychotropic medications; SRD = self-reported disease diagnoses; VQ = validated questionnaires; UQ = unvalidated questionnaires.

Table A6. Full description of studies.

Study	Research Design	Country	Participants	Maximum Sample Size Included in Analyses	Response Rate	Noise Source	High Noise Annoyance Definition	Mental Health Outcomes and Caseness Definition	Confounder	Used Ors	Actual Noise Levels Included in the Model	Note
Baudin, 2018	Cross-sectional	France	Residents living near airports; ≥18	1244	Approximately 60% (not reported exactly)	Aircraft	Verbal 5-point; HA undefined; "Extremely" annoyed to proxy HA.	General mental health: GHQ-12 scores ≥ 3	Gender, age, country of birth, occupational activity, education, marital status, smoking habit, alcohol consumption, number of work-related stress and major stressful life events, household monthly income, sleep duration.	OR = 4.00% CI [1.67–9.55]	Yes; per 10 dB Lden; range unclear.	
Baudin, 2021	Cross-sectional	UK, Germany, Netherlands, Sweden, Italy, Greece, France	Residents living near airports; age ≥ 18	5867 (combined studies)	Unclear	Aircraft	HA_N	Depression and anxiety disorder; antidepressant and anxiolytic drug use	Gender, age, body mass index (BMI), alcohol consumption, smoking habits, physical activity, education level, and country, an interaction term between country and each of the three factors of interest (noise level, noise annoyance and noise sensitivity).	Depression: OR = 1.02 95% CI [0.72–1.44]; Anxiety: OR = 1.48 95% CI (1.08–2.05)	No	Annoyed by aircraft noise at night
Beutel, 2016	Cross-sectional	Germany	Population based; age 35–74	14,635	60.3%	Road traffic, aircraft, railways, industrial, neighbourhood, overall noise; day and night	Verbal 5-point; HA undefined; "Extremely" annoyed to HA.	Depression and anxiety disorder; PHQ-9 scores ≥ 10 and GAD 2 scores ≥ 3	Sex, age, and socioeconomic status	Depression: OR = 1.97 95% CI [1.62–2.39]; Anxiety: OR = 2.14 95% CI [1.71–2.67]	No	OR reported separately for annoyance levels; those reported here are for ppts reporting "extreme annoyance"
Beutel, 2020	Longitudinal	Germany	Population based; age 35–74	14,732	Approximately 65% completed both baseline and follow-up (not reported exactly)	Road traffic, aircraft, railways, industrial, neighbourhood, overall noise; day and night	HA_V	Depression and anxiety disorder; PHQ-9 scores ≥ 10 and GAD 2 scores ≥ 3	Sex, age, socioeconomic status, employment status, and work shift pattern	Depression: RR = 1.06 95% CI [0.97–1.16]; Anxiety: RR = 1.10 95% CI [1.02–1.19]	No	Most conservative estimates selected. Depression: baseline overall noise annoyance at daytime estimate; anxiety: follow-up overall noise annoyance at nighttime estimate.

Table A6. *Cont.*

Study	Research Design	Country	Participants	Maximum Sample Size Included in Analyses	Response Rate	Noise Source	High Noise Annoyance Definition	Mental Health Outcomes and Caseness Definition	Confounder	Used Ors	Actual Noise Levels Included in the Model	Note
Eze, 2020		Switzerland	Population based; age 29–73	4581	Unclear	Road, railways, and aircraft	Numeric 11-point scale; HA undefined	Depression; physician diagnosis, intake of antidepressant medication or having a SF-36 score < 50	Age (years), sex (male/female), educational attainment ($\leq$9 years compulsory education/10–13 years corresponding to secondary education or apprenticeship/>13 years corresponding to tertiary education), area and neighborhood socio-economic position.	OR = 1.04 95% CI [1.00–1.11]	No	Most conservative estimates selected
Floud, 2011	Cross-sectional	UK, Germany, Netherland, Sweden, Italy, Greece	Residents living near airports; age 45–70	4642	Unclear	Aircraft	HA_N	Depression and anxiety disorder; antidepressant and anxiolytic drug use	Gender, age, and body mass index (BMI), alcohol intake, level of physical activity, educational level, smoking.	Depression: OR = 1.00 95% CI [0.67–1.50]; Anxiety: OR = 1.74 95% CI [1.16–2.61]	No	Annoyed by aircraft noise at night was used.
Hammersen, 2016	Cross-sectional	Germany	Population based; age 18–99	19,294	22.1%	Road/air traffic and neighbours	HA_V	General mental health; MHI-5 scores $\leq$ 52	Age, socioeconomic status (SES), and urbanisation grade, (school/vocational education, occupational status, and net equivalent household income used for SES), social support, self-reported chronic disease.	Female: OR = 2.42 95% CI [1.77–3.32]; Male: OR = 2.87 CI [2.01–4.09]	No	
Jensen, 2018	Cross-sectional	Denmark	Residents living in multi-storey houses; age $\geq$ 16	7090	61% (2010 survey) and 57% (2013 survey)	Neighbour and traffic	Verbal 3-point; HA undefined; "Very" annoyed to proxy HA.	General mental health; SF-12 scores $\leq$ 10th percentile (or score of 32.78)	Sex, age, education, marital status, degree of urbanisation, and the Physical Component Summary (PCS) score from SF-12	OR = 2.35 95% CI [1.86–2.97]	No	
Jensen, 2019	Cross-sectional	Denmark	Residents living in multi-storey housing; age $\geq$ 16	3893	56%	Noise from neighbours	Verbal 3-point; HA undefined; "Very" annoyed to proxy HA.	Depression and anxiety; unvalidated questionnaire (Self-reported)	Age, sex, marital status, degree of urbanisation, highest level of completed education, ethnic background, and owner/tenant status	Depression: OR = 2.10 95% CI [1.39–3.18]; Anxiety: OR = 2.60 95% CI [1.73–3.91]	No	

Table A6. *Cont.*

Study	Research Design	Country	Participants	Maximum Sample Size Included in Analyses	Response Rate	Noise Source	High Noise Annoyance Definition	Mental Health Outcomes and Caseness Definition	Confounder	Used Ors	Actual Noise Levels Included in the Model	Note
Maschke, 2007	Cross-sectional	France, Germany, Slovakia, Hungary, Portugal, Italy, Switzerlan, Latvia	Population based; age 18–59	8539	Unclear	Neighbourhood	Verbal 5-points. Unclear how to define *HA*.	Depression; self-reported disease and doctor diagnosed disease	Age, gender, city, traffic noise annoyance, socio-economic-state, consumption of alcohol, smoking behaviour, sports activity, body mass index, satisfaction with residential areas, green areas, The perception of: dampness in dwelling, air quality in dwelling, temperature and heating in winter, daylight in dwelling.	OR = 1.60 95% CI [1.04–2.45]	No	
Okokon, 2018	Cross-sectional	FInland	Population based; age $\geq$ 25	7321	47% (2015 survey) and 45% (2016 survey)	Road	Verbal 5-point; top 3 answers grouped as *HA*	Depression and anxiety disorder; antidepressant and anxiolytic drug use	Age, sex, marital status, employment status and household income level (average yearly income before taxes), alcohol consumption, current smoking status, weekly frequency of leisure-time physical activity, and pet ownership	Depression: OR = 1.15 95% CI [0.82–1.63]; Anxiety: OR = 1.41 95% CI [1.02–1.95]	No	
Schreckenberg, 2010	Cross-sectional	Germany	Residents living near airports; aged 16 and above	2312	61%	Aircraft	Numeric 11-point and verbal 5-point questionnaires used; unclear how to define *HA*	General mental health; SF-12 scores < median SF-36 scores < median; unclear the exact cut-off values	Railway and road traffic sound level, age, gender, socio-economic status, home ownership, residential satisfaction, usual window position in the sleeping room at night, number of hours away from home.	OR = 1.06 95% CI [0.97–1.17]	Yes; LAeq,16 h (categorical: <40, 40–45, 45–50, 50–55, 55–60, $\geq$60)	Most conservative estimates selected (SF-12)
Stansfeld, 2021	Longitudinal	UK	Male population based; age 45–59	2398	89.82% at phase 3 and 70.93% at phase 4	Road	Nonstandard verbal 5-point; top 2 answers grouped as *HA*.	General mental health; 4/5 on the GHQ scale	Age, social class, marital status, employment status, smoking status, BMI, alcohol consumption, physical activity at leisure, and noise at work	OR = 2.47 95% CI [1.00–6.13]	No	

Note: HA = high noise annoyance; HA_N and HA_V are two approaches to identify highly annoyed participants by noise. HA_N uses the top 3 points (8, 9 and 10) of the 11-point numeric noise annoyance scale to identify highly annoyed participants [2,17,26]. HA_V uses the upper two steps (4 "very" and 5 "extremely") of the verbal 5-point response scale to define highly annoyed individuals [2,17,26,28]. LAeq = equivalent continuous sound pressure level; Lden = day–evening–night noise level; dB = decibels; GHQ = General Health Questionnaire; SF-12 = Short-Form 12 survey; PHQ-9 = Patient Health Questionnaire-9; GAD-2 = Generalized Anxiety Disorder-2; MHI-5 = Mental Health Inventory.

Appendix B

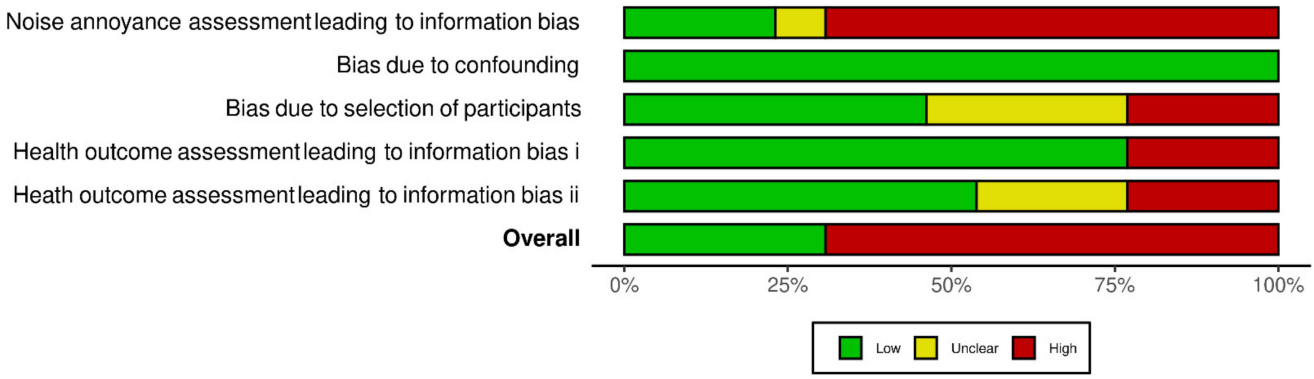

Figure A1. Summary of the risk of bias assessments.

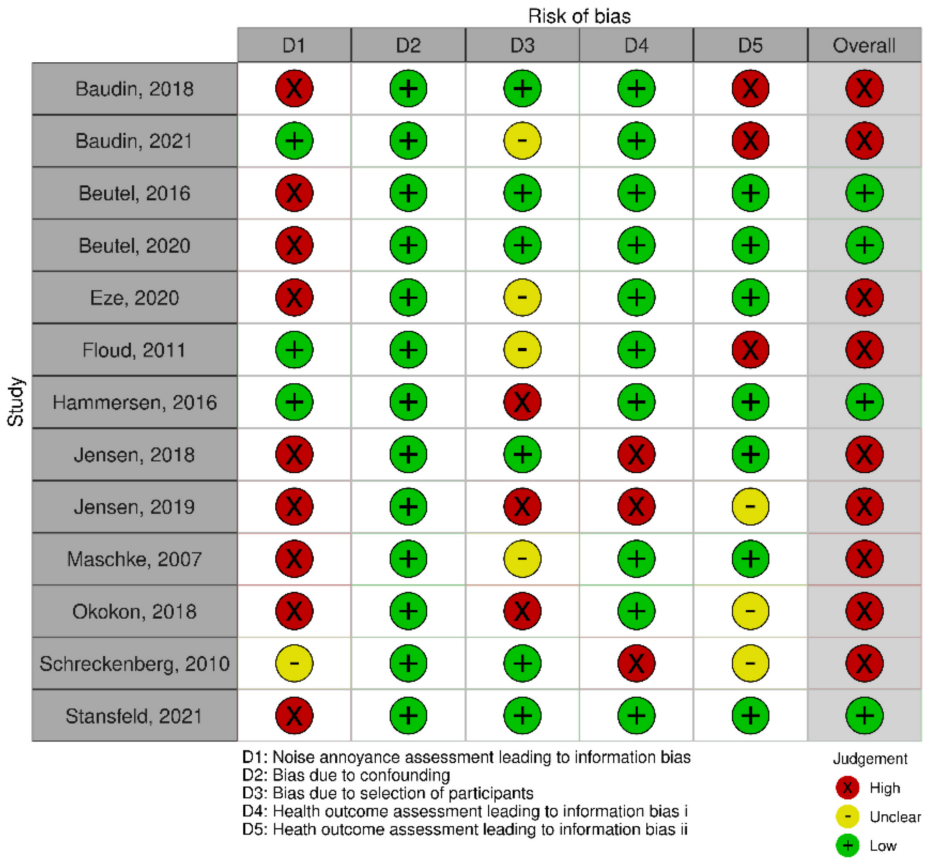

Figure A2. Risk of bias assessment.

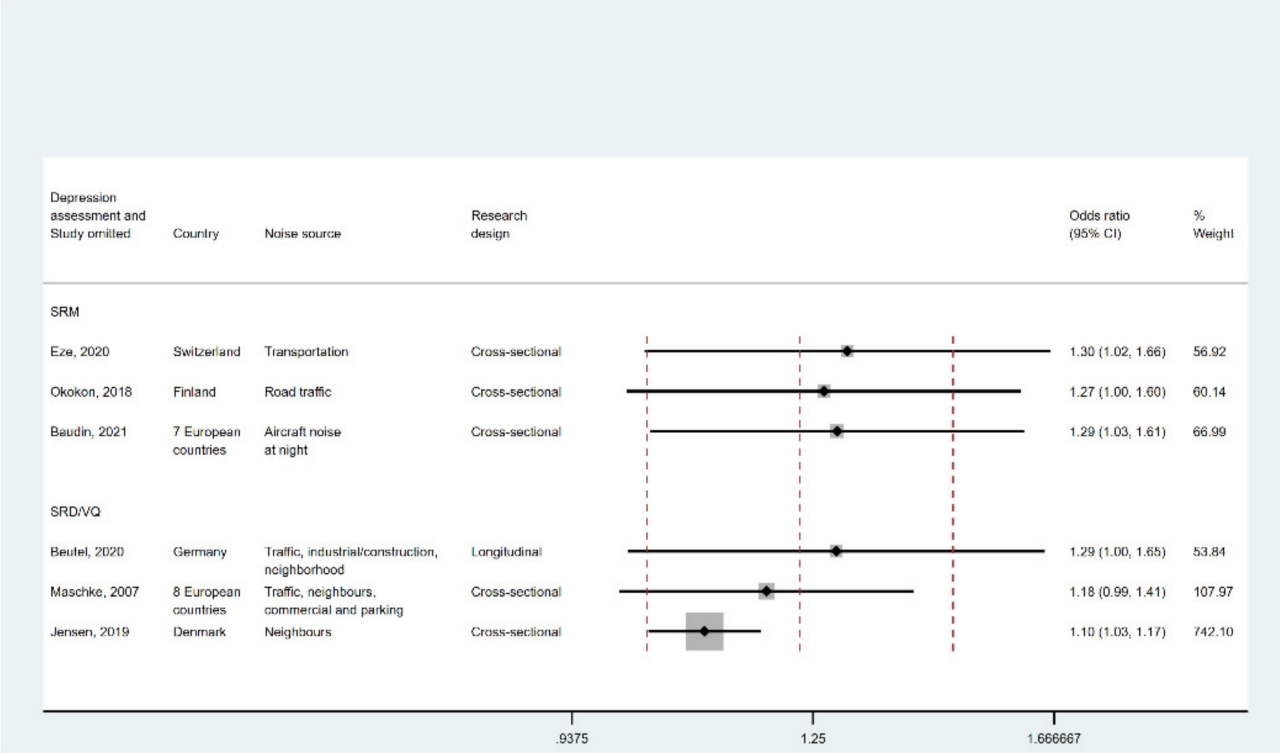

Figure A3. Leave-one-out analysis for identifying outliers in depression studies. Note: weights are from random-effects model.

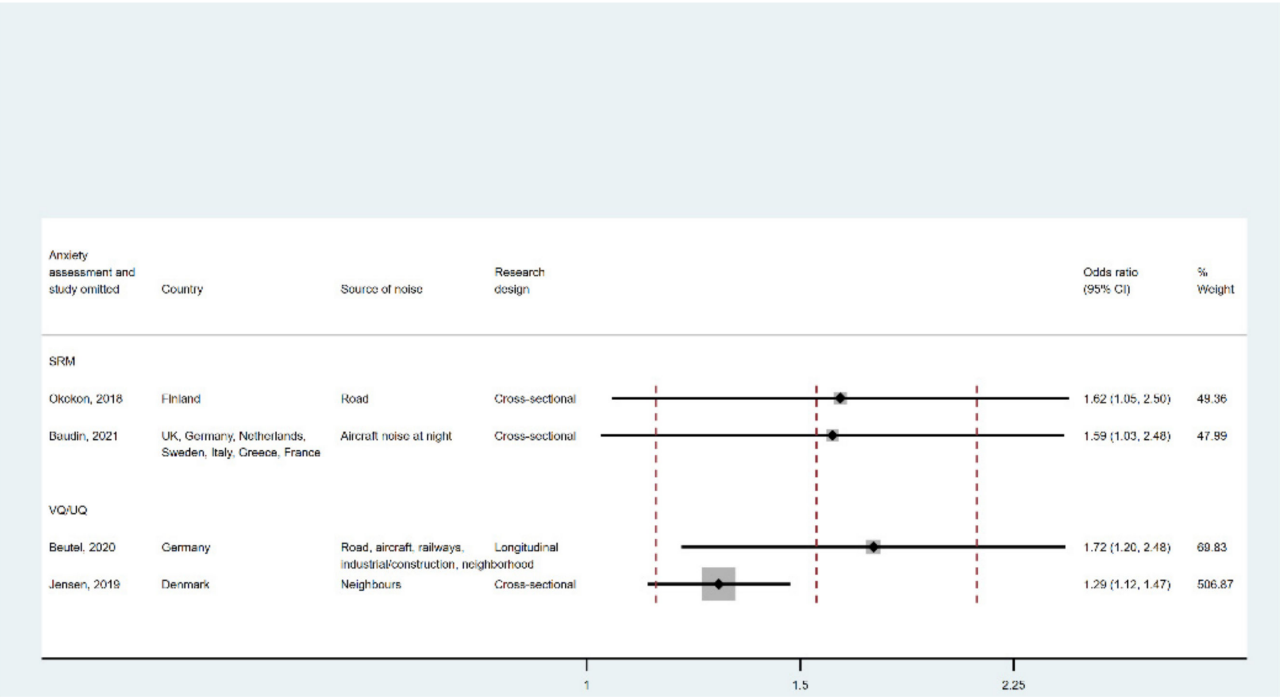

Figure A4. Leave-one-out analysis for identifying outliers in anxiety studies. Note: weights are from random-effects model.

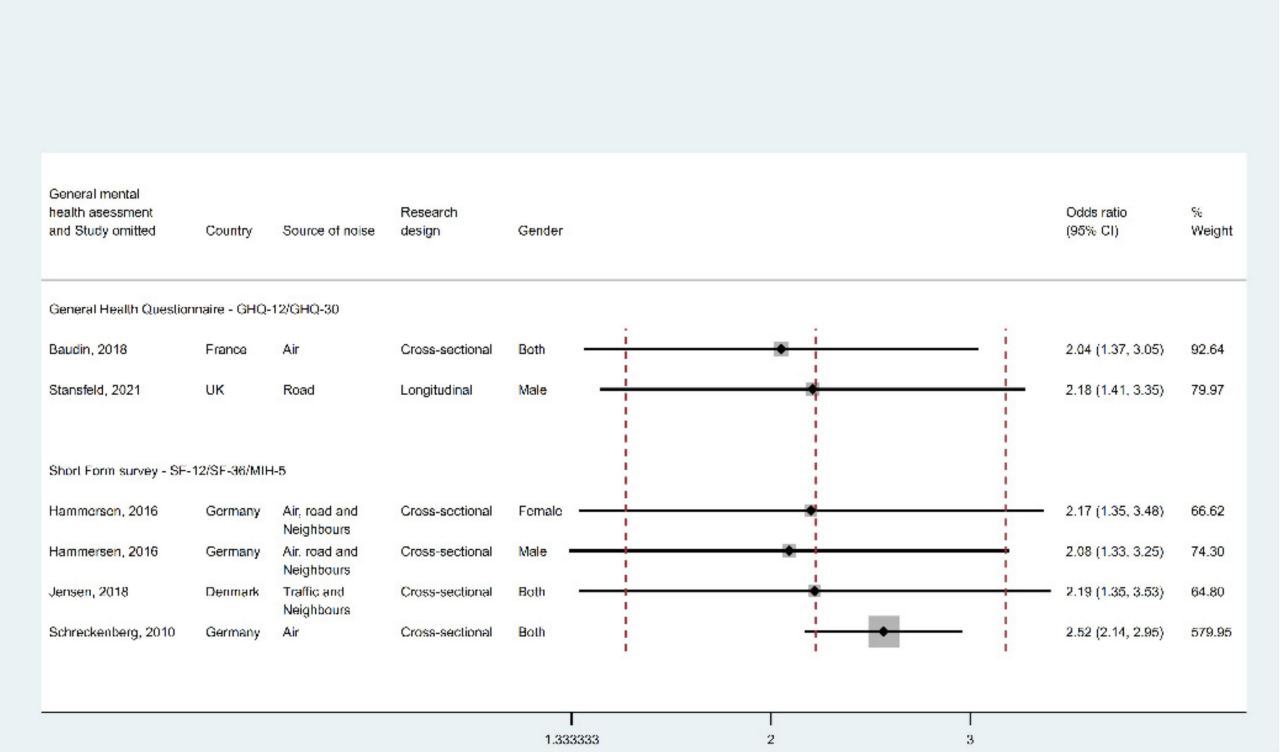

Figure A5. Leave-one-out analysis for identifying outliers in general mental health studies. Note: weights are from random-effects model.

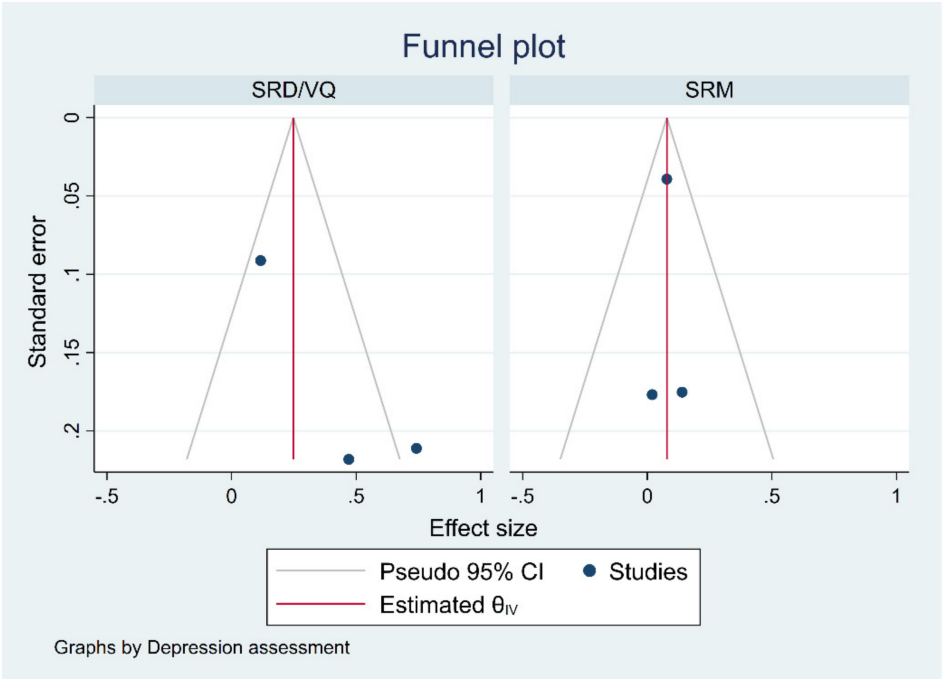

Figure A6. Funnel plot—depression.

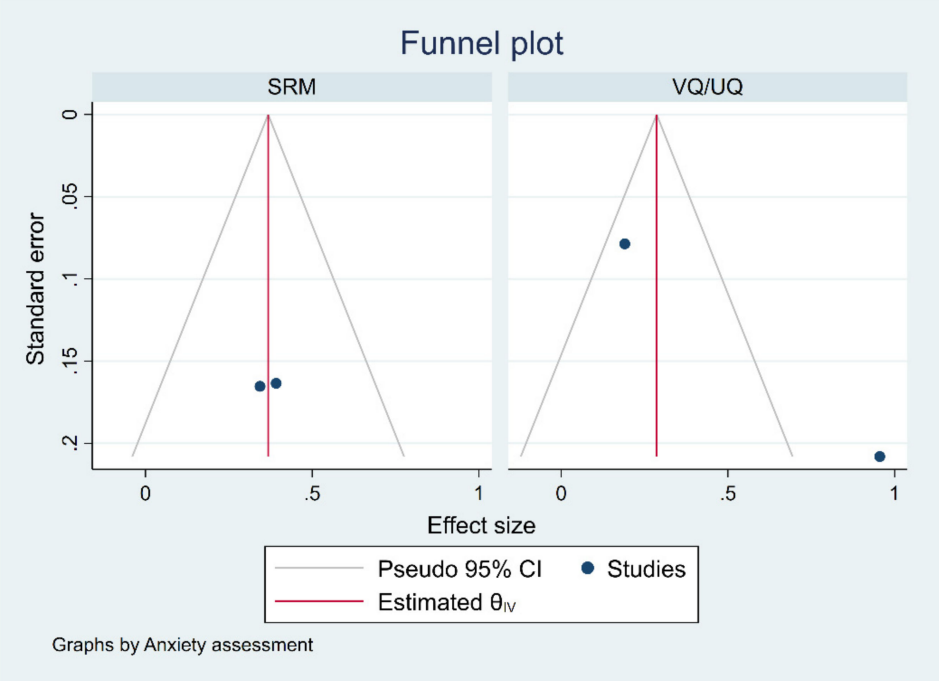

Figure A7. Funnel plot—anxiety disorder.

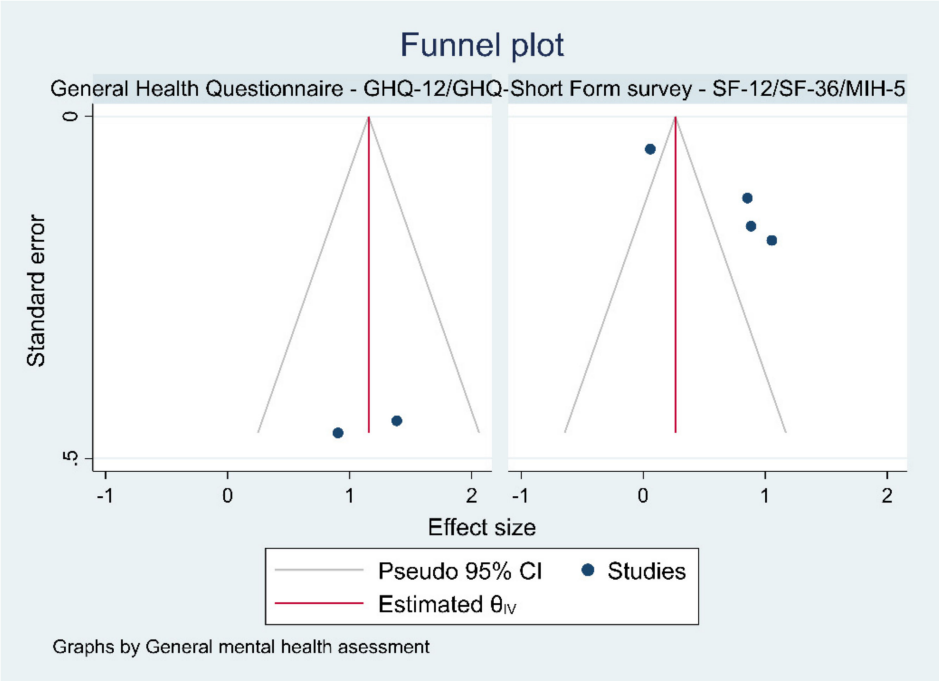

Figure A8. Funnel plot—general mental health.

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REVIEW ARTICLE OPEN

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Noise and mental health: evidence, mechanisms, and consequences

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The recognition of noise exposure as a prominent environmental determinant of public health has grown substantially. While recent years have yielded a wealth of evidence linking environmental noise exposure primarily to cardiovascular ailments, our understanding of the detrimental effects of noise on the brain and mental health outcomes remains limited. Despite being a nascent research area, an increasing body of compelling research and conclusive findings confirms that exposure to noise, particularly from sources such as traffic, can potentially impact the central nervous system. These harms of noise increase the susceptibility to mental health conditions such as depression, anxiety, suicide, and behavioral problems in children and adolescents. From a mechanistic perspective, several investigations propose direct adverse phenotypic changes in brain tissue by noise (e.g. neuroinflammation, cerebral oxidative stress), in addition to feedback signaling by remote organ damage, dysregulated immune cells, and impaired circadian rhythms, which may collectively contribute to noise-dependent impairment of mental health. This concise review linking noise exposure to mental health outcomes seeks to fill research gaps by assessing current findings from studies involving both humans and animals.

Keywords: Vulnerable Populations, Population Based Studies, Exposomics

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NOISE AS A PUBLIC HEALTH CHALLENGE AND TRIGGER OF CHRONIC NON-COMMUNICABLE DISEASES

Noise is one of the most ubiquitous environmental pollutants, as suggested by reports from the World Health Organization (WHO) and the European Environment Agency (EEA) that noise exposure is a major public health threat affecting both physical and mental health [1, 2]. In the European Union alone, estimates indicate that at least 20% of the urban population are affected by the harmful effects of road traffic noise. Consequently, long-term transportation noise levels result in at least 18 million people being highly noise annoyed and further 5 million suffering from high sleep disturbances [2]. In addition, the WHO reported a loss of more than 1.6 million healthy life years annually due to environmental noise exposure in Western European countries [1]. Importantly, annoyance and sleep disturbance are proposed as key drivers of noise-associated non-communicable disease (NCD) onset and progression (Fig. 1) including both physical and mental health conditions [3]. Indeed, noise exposure has been implicated in a wide range of major NCDs including cardiovascular disease, metabolic disease, cancer, and respiratory disease (Fig. 2 provides an overview). We recently reviewed the cerebral consequences of environmental noise exposure in detail, suggesting that noise exposure could be an important but largely unrecognized risk factor for neuropsychiatric outcomes [4]. However, in contrast to the well-established effects of noise exposure on major NCDs, and particularly on cardiovascular disease, its effects on mental health have not been mapped in detail. This is also reflected by the omission of the quantitative details of the harms of noise on mental health consequences in reports by the WHO or the EEA. This is of concern as mental health disorders may contribute substantially to the burden of disease in the population exposed to noise. Thus, this compact review on mental health identifies some areas of future research by evaluating recent findings from human and animal studies.

THE NOISE/STRESS CONCEPT

The association between noise exposure and adverse mental health outcomes involves a complex interplay of psychological and behavioral mechanisms. In accordance with the noise/stress concept developed by Wolfgang Babisch [5], there are two main pathways by which noise exposure causes adverse health effects. The so-called *"direct pathway"*, i.e. exposure to extreme high decibel levels (>100 dB(A)) causing direct ear organ damage, and the

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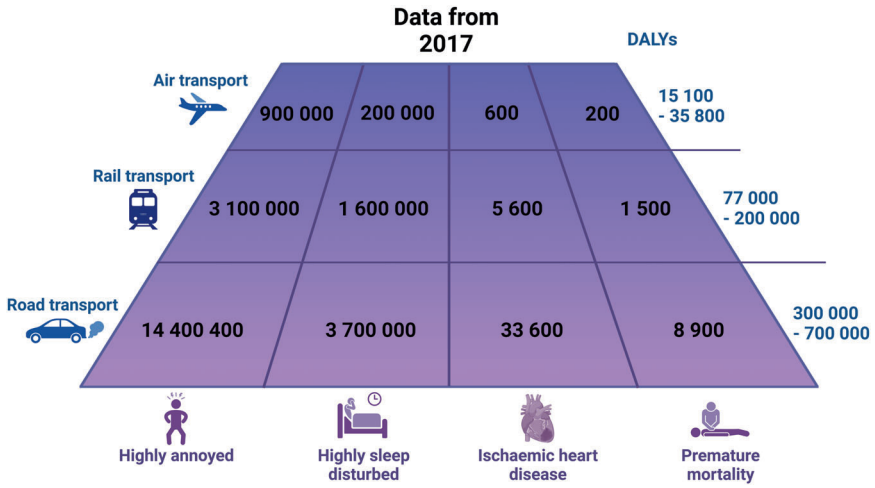

Fig. 1 Key impacts of exposure to unhealthy noise levels, based on the Environmental Noise Directive (END) thresholds, in the European Union in 2017. One DALY equals to the loss of 1 year of healthy life attributed to morbidity, mortality, or both. The most important contributors to the total burden of disease of environmental noise are annoyance and sleep disturbance because of the large number of people affected. Adapted from [70]. DALYs disability-adjusted life years.

so-called *"indirect pathway"* related to the exposure to lower decibel levels in the range of 50–70 dB(A) that impairs daily activities, sleep, and communication. Sleep disturbance is strongly linked to mental health problems, including anxiety and depression [6]. This lower decibel noise leads to sympathetic and endocrine activation and several cognitive and emotional stress reactions, including annoyance, depressive-like states, and mental stress characterized by elevated stress hormone levels and activation of the sympathetic nervous system (Fig. 3). Noise annoyance, characterized by feelings of displeasure and discomfort, can contribute to increased stress levels and the development or exacerbation of mental health issues [3]. This noise-induced pathophysiological cascade favors not only the development and progression of mental health conditions but also of cardiovascular risk factors and cardiovascular disease [3]. Importantly, chronic mental stress per se is a well-known risk factor for both physical and mental health [7]. Even acute nighttime aircraft noise exposure induces takotsubo cardiomyopathy, also known as broken-heart syndrome, a condition triggered by emotional stress and excessive release of stress hormones [8]. In general, chronic noise annoyance/stress may impair adaptation and increase stress vulnerability, leading to decreased stress resistance and coping capacity [3]. In addition, noise exposure may promote maladaptive coping styles as indicated by recent studies demonstrating that traffic noise exposure is associated with increases in smoking, alcohol consumption, and sedentary behavior, all of which can increase the vulnerability to mental health conditions [9–11]. Learned helplessness, characterized by passive resignation due to a perceived lack of control, often arises from chronic exposure to uncontrollable stressors. These exposures trigger a sustained stress response, impacting cognitive processes and leading to a belief that a stress situation is unchangeable, which may increase the vulnerability to mental health problems. Recent research suggests an involvement of learned helplessness when it comes the adverse mental health effects of noise exposure [12].

MECHANISMS OF NOISE-INDUCED MENTAL HEALTH CONSEQUENCES—INSIGHTS FROM ANIMAL MODELS

Several studies in animal models reported that environmental noise can influence inflammatory and oxidative stress pathways in the brain, leading to anxiety and depression-like behavior. A study in mice indicated that traffic noise caused hyperactivity of the hypothalamic–pituitary–adrenal (HPA) axis, leading to lower performance in all cognitive and motor tasks, a reduction of size in the hippocampal formation, medial prefrontal cortex (mPFC), and amygdala, and a reduced neuronal density in the mPFC and dentate gyrus (DG) [13]. Although the results are indicative of cognitive decline, the authors point out that the behavior of mice is suggestive of anxiety-like behavior, providing the connection to mental health decline. The same group also observed increases in anxiety-like behavior, reduced time spent exploring new object/environment even when mice were exposed to a 3000 Hz synthetic sound tone [14]. Neuroinflammation, as shown by increases in IL-1β IL-6 and TNFα in the hippocampus and prefrontal cortex, was observed in mice exposed to a synthetic noise stimulus of 80 dB [15]. These authors also observed depression-like behaviors, envisaged by a decrease in sucrose preference and reduction in times of crossings in the open-field test and the times of rearings (standing on hind legs) in the open-field test. Another study in mice showed that chronic noise exposure caused an increase in malondialdehyde (MDA) levels in the brain, together with a decrease in superoxide dismutase (SOD) and glutathione peroxidase (GPx) activity [16]. These increases in oxidative stress markers were also accompanied by greater circulating cortisol levels and impaired social interactions. A 30-day noise exposure study in rats showed that elevated plasma corticosterone levels are linked to impairment in spatial memory [17]. This was also accompanied by decreases in catalase and glutathione peroxidase activity in the medial prefrontal cortex and hippocampus, suggesting increased oxidative stress. Another study showed that plasma levels of corticosterone, adrenaline, noradrenaline, endothelin-1, nitric oxide and malondialdehyde were increased in rats chronically exposed to intermittent noise, while superoxide dismutase expression was decreased [18]. A study in spontaneously hypertensive rats showed that noise stress resulted in exaggerated glutamatergic responses in the amygdala, pointing to the activation of this important pathway [19].

Our studies in mouse models show that 4-day of exposure to aircraft noise increased levels of pro-inflammatory cytokines IL-6, inducible nitric oxide synthase (iNOS) and cluster of differentiation 68 (CD68) in mouse brains [20]. Down-regulated catalase and neuronal nitric oxide synthase (nNOS) were also observed as key factors of cerebral/neuronal damage in mice exposed to noise. These negative effects were ameliorated by the genetic deletion of the subunit of phagocytic NADPH oxidase (gp91phox), pointing to the important role of immune cell-derived oxidative stress. Interestingly, the effects were more pronounced when noise was applied during the sleeping phase of mice, which correlates well

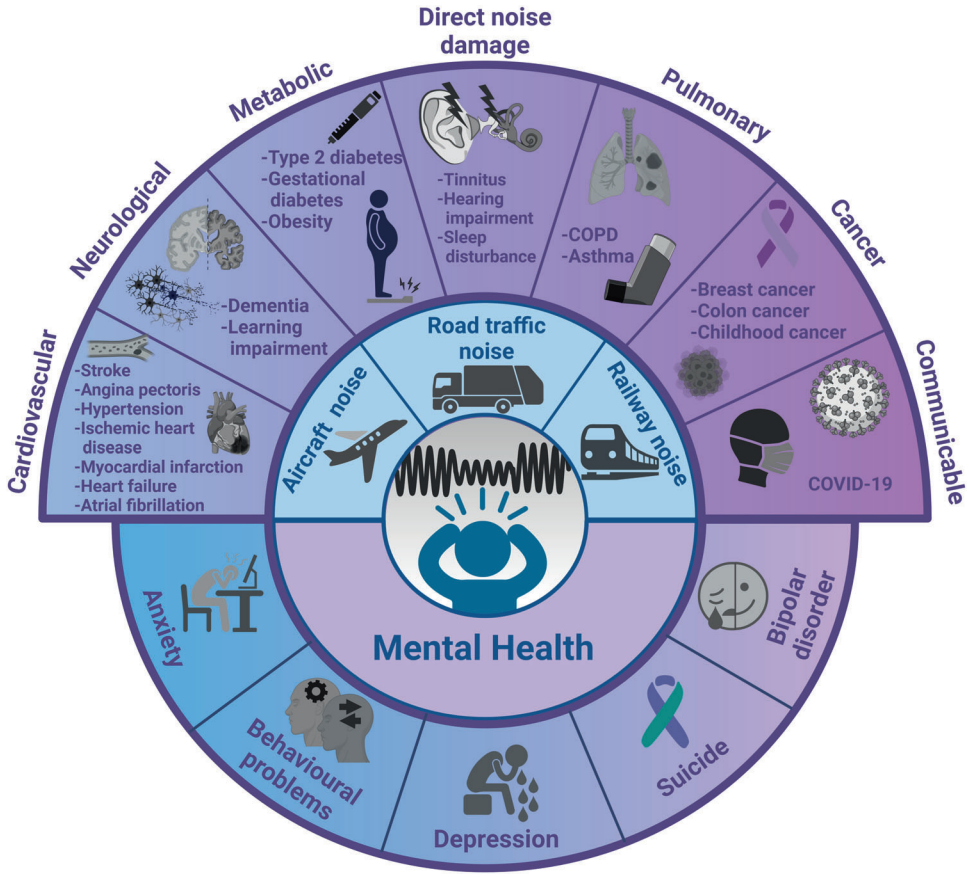

Fig. 2 The effects of noise on different organ systems and on the mental health. Noise from different sources was previously shown to likely affect different organ systems and promote a wide variety of diseases. Detrimental effects of noise can also play a prominent role in onset and progression of many aspects of mental health, like anxiety and depression. Data derived from the following studies: [49–51, 71–87].

with the impairment of circadian rhythms by sleep fragmentation and deprivation [20]. Dysregulation of circadian rhythms seems to represent a hallmark of noise-induced pathomechanisms as it is clear that nighttime noise exposure is much more detrimental for humans than daytime noise [21–23]. We also observed increases in levels of circulating catecholamines (adrenaline and noradrenaline) in a mouse model of 3-day aircraft noise exposure [24]. These experimental data point to a biological state associated with anxiety- and depression-like symptoms, but more preclinical research is needed to draw a strong correlation. Mechanistic findings from animal models have been used to produce a stress response pathway that enables us to better understand the implications of noise exposure on human mental health.

MECHANISMS OF NOISE-INDUCED MENTAL HEALTH CONSEQUENCES—STRESS RESPONSE PATHWAYS

It is generally challenging to identify biochemical correlates of mental health, as mental health is not a single disease, but a collection of complex psychological states with overlapping signs and symptoms. However, anxiety, depression and general mental stress have been associated with activation of certain neurological and endocrine pathways. Anxiety and depression are both correlated with fear and stress via the autonomic nervous system [25]. Noise-induced stress responses activate the hypothalamic–pituitary–adrenal (HPA) axis and the sympathetic nervous system (SNS) [26]. The stress response is triggered when the hypothalamus releases corticotropin-releasing hormone (CRH) and arginine vasopressin (AVP) into the pituitary gland, further stimulating the release of adrenocorticotropic hormone (ACTH) into the circulation. ACTH then signals the adrenal cortex to release glucocorticoids and the SNS signals the adrenal medulla to release catecholamines. The overstimulation of the SNS suppresses the ability of glucocorticoids to modulate the inflammatory response, resulting in the release of pro-inflammatory cytokines [27, 28]. Likewise, chronic stress and the overproduction of glucocorticoids leads to down-regulation of their receptors in immune cells, with a subsequent loss of the ability of glucocorticoids to suppress the activation of inflammatory pathways, e.g. cytokine release, a condition called “cortisol resistance” [29]. The release of pro-inflammatory cytokines is mostly modulated by the activation of the transcription factor nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB) [30]. The inflammatory state can contribute to the maintenance of the fear and stress response by modulating the activity of the brain regions implicated in anxiety, like the amygdala, hippocampus, insula, prefrontal cortex (mPFC), and the anterior cingulate cortex (dACC) [31]. This systemic inflammatory response can in turn exacerbate neuroinflammation [32]. Pro-inflammatory cytokines, such as interleukins 1β/1α/6 (IL-1β, IL-1α, IL-6) and tumor necrosis factor alpha (TNFα), cannot penetrate the blood brain barrier, but can induce inflammatory responses in the circumventricular organs [33]. Microglia and astrocytes become activated and propagate neuroinflammation further by releasing of pro-inflammatory cytokines [34]. Activated immune cells in the brain can disrupt the blood brain barrier and lead to further influx of circulating pro-inflammatory cytokines into the brain [35].

Another important brain region associated with anxiety and depression is the amygdala [36, 37]. During conditions of external

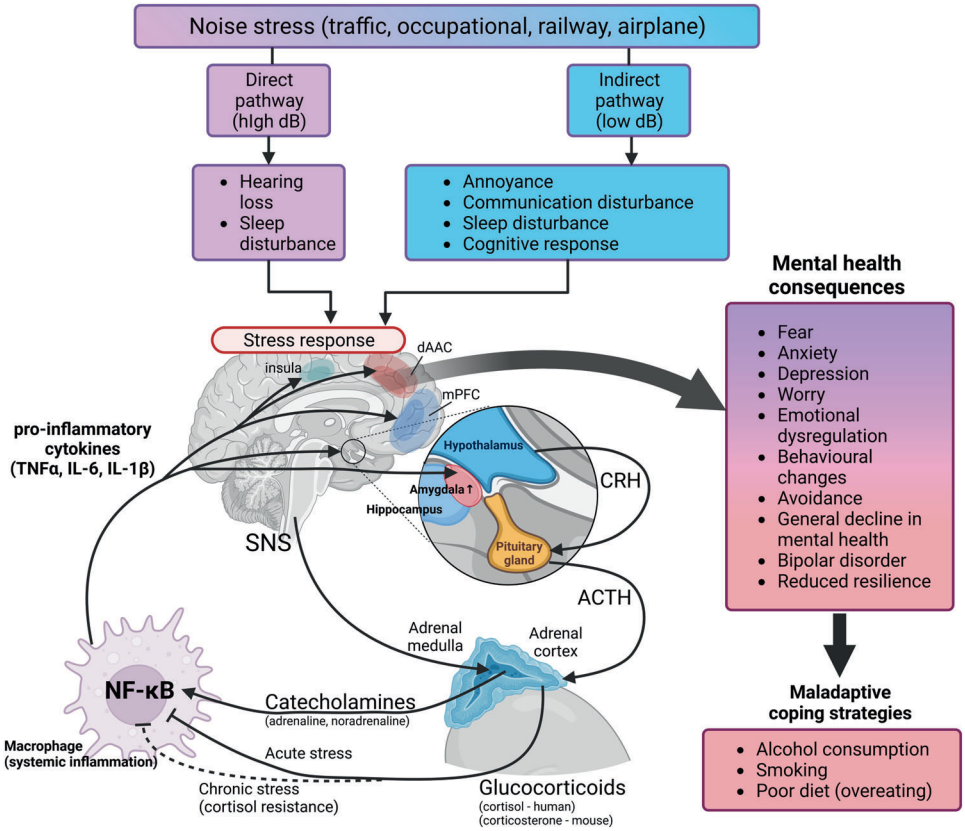

Fig. 3 The noise/stress concept and the associated adverse mental health consequences. Noise induces the stress response through either direct (hearing loss and inner ear damage) pathway or indirect (annoyance and sleep disturbance) pathway. The stress response results in the activation of the hypothalamic–pituitary–adrenal (HPA) axis and an increase in systemic inflammation that becomes neuroinflammation, resulting in the fear and anxiety response. Prolonged exposure to a high stress response leads to maladaptive coping strategies, such as smoking or alcohol consumption. CRH (corticotropin-releasing hormone), ACTH (adrenocorticotropic hormone), NF-κB (nuclear factor kappa-light-chain-enhancer of activated B cells), SNS (sympathetic nervous system), dAAC (dorsal anterior cingulate cortex), mPFC (medial prefrontal cortex), TNFα (tumor necrosis factor alpha), IL-6/1β (interleukin 6/1β). Adapted from [27].

stress, the amygdala can become hyperactivated, increasing the sensitivity to environmental stimuli [38]. The increase in amygdala activity is both a source of neuroinflammation while also being susceptible to systemic inflammation [39, 40]. Oxidative stress and inflammation are almost inseparable in a diseased state, as neuroinflammation is accompanied by oxidative stress in the brain tissue [41, 42]. The release of reactive oxygen species (ROS) is a ubiquitous defense mechanism for any resident immune cells. Neuronal tissue is more susceptible to oxidative stress as neurons have membranes rich in polyunsaturated fats, making them prone to lipid oxidation [43]. In addition, dopamine, norepinephrine, and serotonin are prone to auto-oxidation, impairing synaptic signaling [44]. Nervous tissue also lacks many antioxidant defense mechanisms available to other tissues [45]. The mechanisms of noise-induced stress response are presented in Fig. 3.

EPIDEMIOLOGICAL EVIDENCE

Depression and anxiety

A meta-analysis by Dzhambov and Lercher reported that road traffic noise exposure was associated with 4% higher odds of depression (odds ratio (OR) 1.04, 95% CI 1.03–1.11) as well as 12% higher odds of anxiety (OR 1.12, 95% CI 1.04–1.30 both per 10 dB(A) increase in L_{den}). However, it is important to acknowledge that most of the studies in the meta-analysis were cross-sectional and of lower quality [46]. In agreement, the meta-analysis by Hegewald et al. provided data supporting an association between traffic noise exposure and depression and anxiety [47]. The authors demonstrated a 12% increase in risk of depression (effect size 1.12, 95% CI 1.02–1.23 per 10 dB increase in L_{den}) in response to aircraft noise exposure, while weaker risk increases of 2–3% (not statistically significant) were obtained for road traffic and railway noise exposure. A meta-analysis of nine studies indicated a 9% higher odds of anxiety (OR 1.09, 95% CI 0.97–1.23 per 10 dB increase in L_{den}) due to traffic noise exposure [48]. Higher traffic noise levels were associated with depressive (OR 1.17, 95% CI 1.03–1.32) and anxiety disorders (OR 1.22, 95% CI 1.09–1.38 both per 3.21 dB increase in L_{den}) in the Netherlands Study of Depression and Anxiety ($N = 2980$) [49]. A German case-controlled study investigated depression risk by aircraft, road traffic, and railway noise exposure [50]. For road traffic noise, a linear exposure-risk relationship was determined (OR 1.17, 95% CI 1.10–1.25 for $L_{pAeq,24h} \geq 70$ dB vs. <40 dB). The highest risk increases were shown for aircraft noise ranging at $L_{pAeq,24h} = 50$–55 dB (OR of 1.23, 95% CI 1.19-1.28 for comparison < 40 dB) and for railway noise ranging at $L_{pAeq,24h} = 60$–65 dB (OR 1.15, 95% CI 1.08–1.22 for comparison <40 dB). Interestingly, combining all three exposures (above 50 dB $L_{pAeq,24h}$) resulted in the most excessive risk increase of an OR of 1.42 (95% CI 1.33–1.52 with the reference group being no exposure of 40 dB or more to traffic noise of any source). In the UK Biobank, a positive association between symptoms of nerves, anxiety, tension or depression (OR 1.04, 95% CI 1.01–1.07 for ≥57.8 dB) and bipolar disorder (OR: 1.54, 95% CI 1.21–1.97 for ≥57.8 dB) and road traffic noise exposure was found, while an inverse association occurred for major depression (OR 0.95, 95% CI 0.90-1.00 for 52.1-54.9 dB)

[51]. The incidence of depression due to road traffic, railway, and aircraft noise exposure (L_{den}) as well as noise annoyance was examined in the Swiss cohort study on air pollution and lung and heart diseases in adults (SAPALDIA) [52]. For road traffic (RR 1.06, 95% CI 0.93–1.22) and aircraft noise exposure (RR 1.19, 95% CI 0.93–1.53 both per 10 dB L_{den}) suggestive positive evidence was found for harm, while the effect of noise annoyance was more robust (RR 1.05, 95% CI 1.02–1.08 per point increase). The association between residential noise exposure during pregnancy and later depression hospitalization was examined in sample of 140,456 Canadian women [53]. Herein, strongest risk increases were found for nighttime noise exposure (hazard ratio (HR) 1.68, 95% CI 1.05–2.67 for 70 vs. 50 dB(A) L_{night}). Evidence from a Korean study ($N = 45,241$) suggested self-reported exposure to occupational noise and vibration elevated the odds of anxiety in both men (OR 2.25, 95% CI 1.77–2.87) and women (OR 2.17, 95% CI 1.79–2.61 both vs. no occupational exposure to noise and vibration) [54]. Interestingly, in 2,745 subjects from the Heinz Nixdorf recall study from Germany, there was a pronounced decrease in cognitive function in response to traffic noise when comparing depressed vs. non-depressed subjects, suggesting that those with existing mental health conditions may be more vulnerable to the adverse consequences of noise exposure [55]. Suggestive evidence for an association between the use of psychotropic drugs including sleep medication, anxiolytics, and antidepressants and levels of traffic noise, noise annoyance, and sensitivity was shown by a Finnish study including 7321 subjects [56]. Results from the German Gutenberg Health Study ($N = 11,905$) indicated an association between noise annoyance due to various sources and the incidence of depression, anxiety, and sleep disturbance [57]. While data from 4508 US adolescents from an urban area indicated an association between living in a high-noise area and later bedtimes, a weaker association for depression and anxiety was found [58]. In a cohort of 2,398 men from the UK, road traffic noise exposure (OR 1.82, 95% CI 1.07–3.07 for 56–60 dB(A)), high noise annoyance (OR 2.47, 95% CI 1.00-6.13), and high noise sensitivity (OR 1.65, 95% CI 1.09-2.50) were associated with incident psychological ill-health, which was determined by a questionnaire that predominantly measures depression and anxiety [59].

Suicide

The Swiss National Cohort examined the association between source-specific transportation noise and suicide [60]. The authors demonstrated that road traffic and railway noise was associated with total suicides (HR 1.040, 95% CI 1.015–1.065 and HR 1.022, 95% CI 1.004–1.041, respectively per 10 dB L_{den}). In contrast, this association was weaker for aircraft noise as observed risk increases starting from 50 dB were masked by an inverse association in the very low exposure range from 30 to 40 dB (Fig. 4). In the city of Madrid, short-term exposure to traffic noise was associated with emergency hospital admissions due to anxiety, dementia, and suicides [61]. Higher nighttime noise exposure was associated with elevated risks of suicide death in younger adults (HR 1.32, 95% CI 1.02–1.70), older adults (HR 1.43, 95% CI 1.01-2.02), and adults with mental illness (HR 1.55, 95% CI 1.10–2.19 all per interquartile range increase) in a Korean study ($N = 155,492$) [62].

Behavioral problems in children and adolescents

In the Danish National Birth Cohort study ($N = 46,940$), a 10 dB increase in road traffic noise exposure from birth to 7 years of age was associated with a 7% increase (95% CI 1.00–1.14) in abnormal versus normal total difficulties scores, 5% (95% CI 1.00–1.10) and 9% (95% CI 1.03–1.18) increases in borderline and abnormal hyperactivity/inattention subscale scores, respectively, and 5% (95% CI 0.98–1.14) and 6% (95% CI 0.99–1.12) increases in abnormal conduct problem and peer relationship problem subscale scores, respectively (assessed by the parent-reported

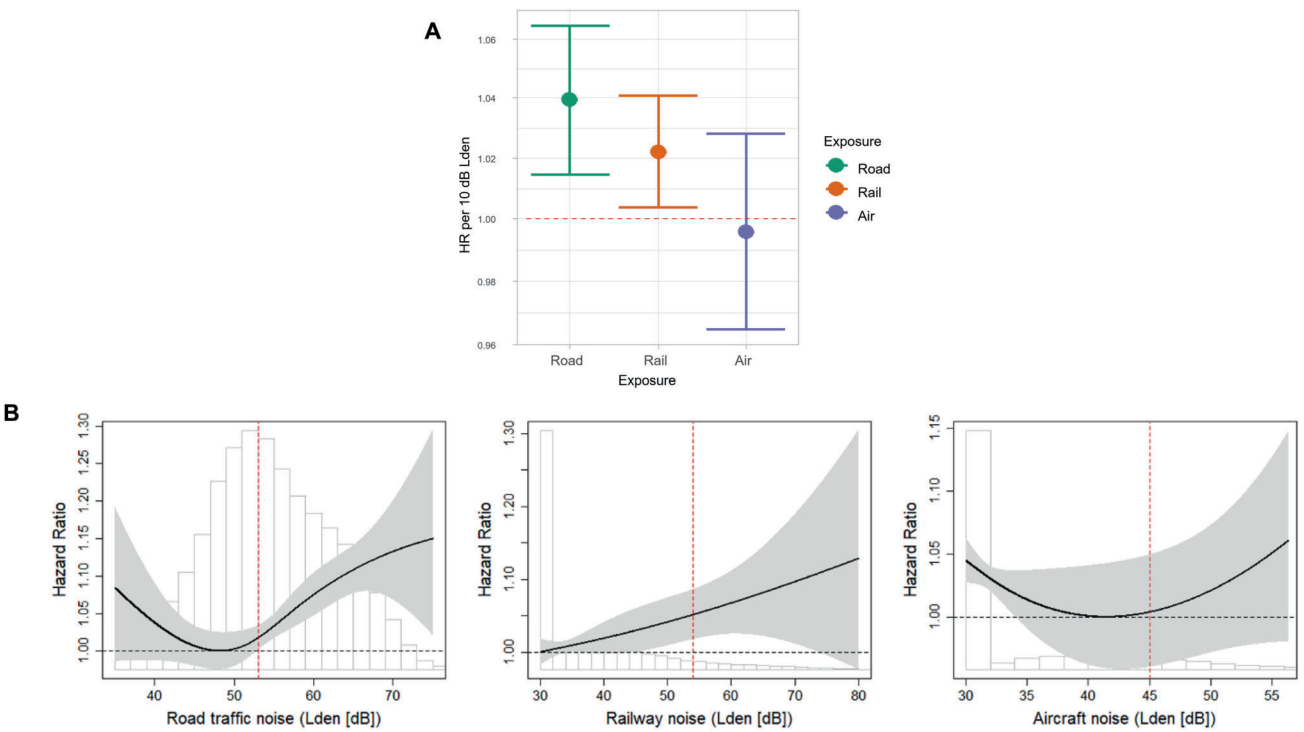

Fig. 4 Risk of suicide and transportation noise. A Association (hazard ratios and 95% confidence interval) between transportation noise source (L_{den}) and mortality from all intentional self-harm (ICD-10: X60–84, excl. ICD-10 ×61.8, X61.9, X81–82) after multivariable adjustment including $PM_{2.5}$ exposure. **B** Exposure-response relationships for the association between transportation noise source (L_{den}) and mortality from intentional self-harm (ICD-10: X60–84, excl. ICD-10 ×61.8, X61.9, X81–82). Vertical dashed red lines show source-specific WHO guideline levels: road traffic = 53 dB, railway = 54 dB, aircraft = 45 dB. Adapted from [60] with permission.

Strengths and Difficulties Questionnaire) [63]. Likewise, among schoolchildren in China, residential road traffic noise exposure was associated with increases in total/abnormal difficulties score, emotional problems, and behavioral concerns [64]. In a cohort of 886 adolescents in Switzerland aged 10–17, cross-sectionally analyzed peer relationship problems increased by 0.15 units (95% CI 0.02–0.27) per 10 dB increase in road traffic noise exposure [65]. However, this relationship was absent in longitudinal analysis. In preschool children in the city of São Paulo ($N = 3385$ children at 3 years of age and $N = 1546$ children at 6 years of age), community noise exposure above L_{den} of 70 dB and L_{night} of 60 dB was associated with impaired behavioral and cognitive development [66]. In contrast, no association was observed between prenatal or childhood road traffic or total noise exposure and emotional, aggressive, and attention-deficit/hyperactivity disorder-related symptoms in children from two European (Spain and Netherlands) birth cohorts [67]. A positive association between noise exposure at school and attention-deficit/hyperactivity disorder-related symptoms was found in a study of children aged 7–11 years in the city of Barcelona [68].

FUTURE RESEARCH NEEDS AND CONCLUSIONS

Noise exposure likely has effects on mental health since the brain represents the primary target organ of noise-mediated effects. While the effects may seem minor when examining human studies, the public health implications are significant. This is evident in reports from the WHO and the EEA, which highlight that environmental stressors such as noise have substantial and continuous impacts on large segments of the population [1, 2]. Some direct adverse phenotypic changes in brain tissue by noise (e.g. neuroinflammation, cerebral oxidative stress), feedback signaling by remote organ damage, dysregulated immune cells, and impaired circadian clock may also play important roles in noise-dependent impairment of mental health. Based on the mechanistic findings on noise research, it is evident that there is a substantial pathomechanistic overlap with mental health conditions, such as depression, that are all linked to cerebral oxidative stress and inflammation. By sharing pathomechanisms, noise can either promote the development of mental health problems or increase their severity in a bonfire fashion.

Future research needs include: preclinical noise research should deepen the mechanistic understanding of noise-induced mental health problems, allowing for drug-based interventions at different levels that target the detrimental neuronal signaling cascade. In addition, biomarkers of noise-triggered mental health harms should be identified using validated animal models in order to allow early diagnosis of vulnerable groups at higher risk of noise-inflicted mental disease. Clinical noise research should further extend the evidence base of exposure-mediated mental health effects and also investigate non-pharmacological mitigation strategies (e.g. coping mechanisms for improved resilience) such as exercise, meditation, green space availability, co-exposures, and mental health training [69]. Additional research is also needed on the benefits of technology to reduce noise (e.g noise cancellation headphones, active noise cancellation home kits, etc).

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GeoHealth

RESEARCH ARTICLE

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Advancing Understanding on Greenspace and Mental Health in Young People

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Key Points:

- Greenspace is associated with lower mental health prevalence among young people
- Greenspace interventions need to consider community structures, specifically rurality
- The highest prevalence of substance use disorders occurred in communities with low greenspace quantity and low greenspace accessibility

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Mental distress among young people has increased in recent years. Research suggests that greenspace may benefit mental health. The objective of this exploratory study is to further understanding of place-based differences (i.e., urbanity) in the greenspace-mental health association. We leverage publicly available greenspace data sets to operationalize greenspace quantity, quality, and accessibility metrics at the community-level. Emergency department visits for young people (ages 24 and under) were coded for: anxiety, depression, mood disorders, mental and behavioral disorders, and substance use disorders. Generalized linear models investigated the association between greenspace metrics and community-level mental health burden; results are reported as prevalence rate ratios (PRR). Urban and suburban communities with the lowest quantities of greenspace had the highest prevalence of poor mental health outcomes, particularly for mood disorders in urban areas (PRR: 1.19, 95% CI: 1.16–1.21), and substance use disorders in suburban areas (PRR: 1.35, 95% CI: 1.28–1.43). In urban, micropolitan, and rural/isolated areas further distance to greenspace was associated with a higher prevalence of poor mental health outcomes; this association was most pronounced for substance use disorders (PRRUrban: 1.31, 95% CI: 1.29–1.32; PRRMicropolitan: 1.47, 95% CI: 1.43–1.51; PRRRural 2.38: 95% CI: 2.19–2.58). In small towns and rural/isolated communities, poor mental health outcomes were more prevalent in communities with the worst greenspace quality; this association was most pronounced for mental and behavioral disorders in small towns (PRR: 1.29, 95% CI: 1.24–1.35), and for anxiety disorders in rural/isolated communities (PRR: 1.61, 95% CI: 1.43–1.82). The association between greenspace metrics and mental health outcomes among young people is place-based with variations across the rural-urban continuum.

Plain Language Summary Poor mental health outcomes are increasing among young people, stressing the need for community-level mental health interventions. This analysis explored the association between greenspace and mental health prevalence among young people. Our analysis found that greenspace is associated with lower mental health prevalence. However, the most effective greenspace interventions (i.e., improving greenspace access, increasing greenspace quantity) may vary with rurality. Greenspace quantity interventions may be most beneficial in urban and suburban neighborhoods; greenspace accessibility interventions may benefit mental health in urban, micropolitan, and rural/isolated areas, and greenspace quality interventions aimed at increasing biodiversity should focus on small towns and rural/isolated communities.

1. Introduction

Poor mental health among adolescents, including depression (Keyes et al., 2019; Thorisdottir et al., 2017), anxiety (Duffy et al., 2019; Eisenberg, 2019; Thorisdottir et al., 2017), self-harm, and suicide (Duffy et al., 2019; Eisenberg, 2019) have increased substantially in recent years in the United States. Observed increases in poor mental health outcomes among children, adolescents, and young adults have been especially pronounced for females (Keyes et al., 2019; Mercado et al., 2017; Thorisdottir et al., 2017), individuals who identify as LGBTQ+ (Fish et al., 2021; Ormiston & Williams, 2022), adolescents of color (Lindsey et al., 2019), and Hispanic individuals (Runkle et al., 2021). To better inform targeted mental health interventions, additional research into widely available community mental health resources, such as greenspace, are needed for this population.

Past greenspace mental health research among the general population (i.e., individuals of all ages) has found greenspace is associated with population-level reductions in anxiety (Beyer et al., 2014; de Vries et al., 2016; Nutsford et al., 2013), depression (Beyer et al., 2014; McEachan et al., 2016), mood disorders (de Vries et al., 2016; Nutsford et al., 2013) and general mental health and wellbeing (mental illness) (Feng & Astell-Burt, 2017a; Houlden et al., 2019; Wheeler et al., 2015; Zhang et al., 2020). Additionally, increases in greenspace

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quantity may be beneficial for addiction treatments and helping reduce addiction-related cravings (Berry et al., 2021; Martin et al., 2019). Among children, recent research has focused on investigating the associations between greenspace exposure and childhood mental well-being through the lens of attention and behavior (Bijnens et al., 2022; Luque-García et al., 2022). Findings suggest greenspace is associated with better attention, both in terms of focusing on one specific task and the ability to continue focusing despite external distractions, among adolescents (ages 13–17) (Bijnens et al., 2022). Further research suggests that contact with greenspace may be beneficial for child neurological development (Luque-García et al., 2022), and prolonged exposure to greenspace in childhood and adolescence is associated with a lower risk of developing psychiatric disorders in adulthood (Engemann et al., 2019). Contextual factors (e.g., back-yard, perceived safety) (Mueller et al., 2023; Zhang et al., 2020, p. 202) impact this association, stressing the need for place-based greenspace and mental health analyses.

A growing body of research considering multiple greenspace metrics (i.e., greenspace quality, quantity, accessibility) suggests that greenspace quality (measured as user-perceived) (Feng & Astell-Burt, 2017a, 2017b; Feng et al., 2020; Lyons et al., 2018), and accessibility (measured as availability of greenspace) (Markevych et al., 2014; Zach et al., 2016) may be more important than neighborhood greenspace quantity for children, adolescents and young adults mental wellbeing. Findings further indicate that the association between greenspace and mental health may change as individuals age through adolescence and young adulthood. Feng and Astell-Burt (2017a) suggest that the mental health benefits of greenspace for young people strengthen as youth transition into adolescence and young adulthood, and that greenspace quality is especially important in this relationship.

Greenspace analyses investigating the role of the rural-urban continuum suggest that urban areas have far better accessibility to public greenspaces (Wolff et al., 2020). In contrast, rural communities tend to have a higher prevalence of private home gardens and backyards (Dennis & James, 2017). Furthermore, Shanahan et al. (2017) found that urban communities with more public greenspaces tended to use greenspace at higher rates and reported more satisfaction with the public greenspaces than urban communities with a lower prevalence of public greenspaces. Among children, higher quantities of public greenspace in urban areas were associated with higher intelligence and lower prevalence of externalizing behaviors (e.g., aggression). However, this association was not significant in suburban or rural communities, suggesting place may play an important role (Bijnens et al., 2022). Little research has been conducted investigating the mental health of young people with regard to greenspace across the rural-urban continuum.

This ecological study aims to further the understanding of the greenspace-mental health association among young people in five distinct urbanities (i.e., urban, suburban, micropolitan, small towns, rural/isolated). We apply publicly available greenspace data sets, which were used to generate greenspace quantity, quality, and accessibility metrics. We hypothesize that place plays an essential role in the greenspace-mental health association among young people; such that neighborhoods with higher quantities and better accessibility of greenspace will be associated with a lower prevalence of poor mental health outcomes; particularly in urban and metropolitan neighborhoods. We further hypothesize that neighborhoods in small towns and rural communities with better greenspace quality will lower the prevalence of poor mental health outcomes among young people. The exploration of multiple greenspace metrics, in addition to an administrative emergency-department mental health data set, furthers understanding of the greenspace-mental health association. Furthermore, considering a suite of mental health outcomes (i.e., mood disorders, anxiety, substance use disorders) provides important context for targeted health interventions. Given that greenspace may function as widely available and publicly accessible preventative mental health care, a better understanding of these associations and how they vary with rurality is critical.

2. Methods

2.1. Study Area

North Carolina is a state in the southeastern United States characterized by a humid climate, with hot summers and moderately cold winters (Kunkel, 2022) and varied topography, with the Appalachian Mountains in the western region of the state, and the Atlantic Ocean on the eastern edge of the state. North Carolina is home to 10.4 million residents, of which 62.2% are white, 20.5% are Black or African American, and 10.7% identify as Hispanic or Latino (US Census, 2022). Young people (individuals 24 and under) make up 33.8% of the state population (US Census, 2022). In North Carolina, mental health providers can meet only 13% of the state's mental health care

needs, compared to 27.7% nationally (KFF, 2021), further highlighting the need for community-level mental health interventions to reduce these mental health care needs.

2.2. Health Data

Mental health outcomes were derived from emergency department (ED) visit data, which were obtained from the North Carolina Disease Event Tracking and Epidemiologic Collection Tool (NC DETECT) (NC DETECT, 2021) for 2016–2019 through an ongoing data use agreement. NC DETECT provides complete spatial coverage (includes data from all EDs in North Carolina) and temporal coverage (includes patients' date of admission to the ED) of ED visits in North Carolina (NC DETECT, 2021). NC DETECT data has been used in a variety of studies, including identifying spatial trends in mental health (Ryan et al., 2022; Sugg et al., 2022), extreme heat and ED visits (Fuhrmann et al., 2016; Kovach et al., 2015; Sugg et al., 2016), and investigating air mass type and migraine risk (Elcik et al., 2017). NC DETECT data has been validated as an accurate state-wide health data set (Hakenewerth et al., 2009). For this analysis, data were restricted to ED visits of individuals aged 24 and younger, producing a data set of 5,357,703 total ED visits between January 2016 and December 2019, of which 575,536 (10.7%) were related to a mental health or behavioral concern.

Using the provided International Classification of Diseases 10-CM codes (ICD-10), ED data were coded (SM Table 1) to isolate five mental health outcomes: (a) anxiety, (b) depression, (c) mental and behavioral disorders (an aggregated category including any mental health or behavioral concern), (d) mood disorders, and (e) substance use disorders. Substance use disorders included any substance-related ED visit (i.e., alcohol, opioids, etc.). Mental and behavioral disorders include any mental-health related concern, such as anxiety, depression, mood disorder, and substance use disorder visits.

The unit of analysis was the Zip Code Tabulation Area (ZCTA) level, which is the finest spatial resolution available for the NC DETECT health data set. ZCTA's are a US Census Bureau spatial geography relating to mailing postal codes, which do not always have a spatial component (i.e., P.O. Box zip codes) (US Census Bureau, 2022). As such, individual ED data was converted from zip code (U.S. postal service) to ZCTA (U.S. Census geography) when appropriate (AAFP, 2022). ZCTAs are considered a categorization of a neighborhood when examining neighborhood and health associations (Duncan & Kawachi, 2018), and have been shown to capture community health patterns more accurately, compared to county-level analyses (Jones & Kulldorff, 2012). In NC, there are 802 ZCTAs, which have a median area of 115 km^2 (SD 147 km^2). Mental health outcomes were coded in RStudio, version 2022.07.1 (RStudio Team, 2022).

2.3. Greenspace Data

For this analysis, greenspace was identified using two publicly available greenspace data sets: the Protected Area Database of the United States (PAD-US) (USGS, 2020) and the Trust for Public Land's ParkServe data set (The Trust for Public Land, 2021) (Figure 1). PAD-US is a spatial shapefile data set with polygons delineating the boundaries of all government-managed lands (e.g., wildlife refuges, national forest land, historical sites); data was collected in 2019. Following guidance from Browning et al. (2022), greenspace selection was restricted to remove any non-public greenspaces (e.g., military bases, indigenous lands) from the spatial data set, producing a data set of publicly accessible government-managed greenspaces (Browning et al., 2022; Runkle, Matthews, et al., 2022). ParkServe is a spatial shapefile data set comprising polygons outlining the boundaries of all public parks (e.g., local and city parks) (The Trust for Public Land, 2021); data was collected in 2020. No additional selection criteria were applied to the ParkServe data set. Both data sets were combined to create one spatial greenspace data set, depicting the boundaries of all publicly accessible greenspaces in NC, in ArcGIS Pro 3.0.0 (ESRI, 2022) (Figure 1). This combined spatial data set was used to generate the following greenspace metrics for each community (i.e., ZCTA):

1. **Greenspace quantity** considers the total amount of public greenspace per ZCTA. For this analysis, greenspace quantity was operationalized as two metrics: (a) *Percent Greenspace* and (b) *Greenspace per person* (Runkle, Matthews, et al., 2022) (Table 1). Calculations were made in ArcGIS Pro 3.0.0 (ESRI, 2022).
2. **Greenspace accessibility** was operationalized as one metric: *Greenspace distance* (Table 1), determined as the distance to the nearest greenspace from the population-weighted mean center of each ZCTA. Calculations were made in ArcGIS Pro 3.0.0 (ESRI, 2022).

Table 1
Summary of Greenspace Metrics Considered in This Analysis

Greenspace Metric	Operationalized at ZCTA[a]	Calculated Using	Data Source(s)	Exclusion Criteria	Hypothesized Association
Greenspace quantity					
Percent Greenspace	Percent greenspace land cover	Tabulate Intersection	PAD-US and ParkServe	Excluded due to multicollinearity with Greenspace per Person	Higher quantities of percent greenspace will be associated with a lower incidence of poor mental health
Greenspace per Person	Greenspace area/ individual 24 and younger	Tabulate Intersection; total area of greenspace divided by total population (24 and younger)	PAD-US, ParkServeACS 2018		Higher quantities of greenspace per person will be associated with a lower incidence of poor mental health
Greenspace Accessibility					
Greenspace Distance	Distance to nearest greenspace from population weighted mean center	Euclidean Distance	PAD-US and ParkServe		Shorter distances to greenspace will be associated with a lower incidence of poor mental health
Greenspace quality					
Average Google Review	Average of available google reviews (0–5) of greenspaces	Reviews manually retrieved from google.com; averaged	Google	Included in state-wide model, excluded from stratified, effect modification analyses; not standardized	Higher average google reviews will be associated with a lower incidence of poor mental health
Nearest Google Review	Google review (0–5) of nearest greenspace from population weighted centroid	Reviews manually retrieved from google.com	Google, PAD-US and ParkServe	Included in state-wide model, excluded from stratified, effect modification analyses; not standardized	Higher near google reviews will be associated with a lower incidence of poor mental health
Perimeter Area Ratio (PAR)	Ratio of total greenspace perimeter to total greenspace area	Determined the perimeter using Summarize Within, divided the perimeter by the area of public greenspace	PAD-US and ParkServe		Lower PAR values (higher quality) will be associated with a lower incidence of poor mental health

[a]ZCTA: All operationalized metrics are calculated for each Zip Code Tabulation Areas (ZCTA) unit.

3. **Greenspace quality** was operationalized as three metrics: (a) *Perimeter: Area Ratio (PAR)*, (b) *Average Google Review*, and (c) *Nearest Google Review* (Table 1). The PAR was included to capture greenspace patchiness (Fonseca, 2008), which serves as a proxy for biodiversity, with a lower PAR indicating less greenspace patchiness, which can benefit flora and fauna in natural spaces (Helzer & Jelinski, 1999). For this analysis, a low PAR value was considered indicative of higher quality greenspace—as the perimeter length is substantially less than the area—suggesting the greenspace is not disrupted with intermittent development (e.g., road). ZCTAs with no public greenspace were categorized as poor quality. The *average Google review* was calculated by averaging all available average greenspace Google reviews for each ZCTA, producing one value for each ZCTA. The *nearest Google review* was determined by identifying the nearest greenspace's average Google review from the population-weighted mean center of each ZCTA (see greenspace accessibility) (Table 1) (SM Figure 3).

2.4. Covariates

Analyses were adjusted for ZCTA race and socio-economic status using the Index of the Concentration of Extremes (ICE) (Krieger et al., 2016), a series of indicators derived by analyzing the spatial distribution of income and race using US Census Data (US Census, 2018), producing community-level race and income metrics (Krieger et al., 2016). The first metric, **ICE: Income**, measures community income extremes by comparing how many

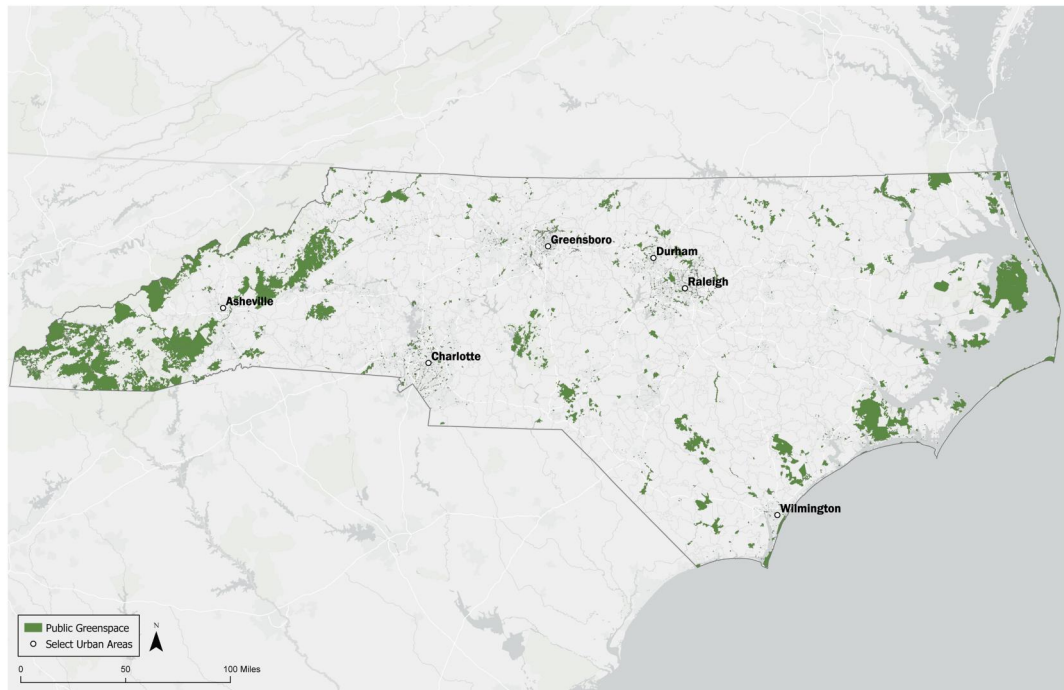

Figure 1. Map depicting the spatial distribution of public greenspace in North Carolina. Greenspace data is from the Protected Area Database of the United States (PAD_US) and the Trust for Public Land's ParkServe data set.

households make over $100,000 per year to how many make under $25,000 per year. The second metric, **ICE: Race**, captures the racial composition of a community by comparing the number of Black residents to the number of white residents. ICE metrics were operationalized as tertiles (Dyer et al., 2022; Krieger et al., 2016; Wallace et al., 2019): (a) predominately low income (ICE: Income) and predominately Black (ICE: Race), (b) mixed-income (ICE: Income) and mixed race (ICE: Race), and (c) predominantly high income (ICE: Income) and predominantly white (ICE: Race) (SM Figure 1).

Mental Health Professional Shortage Areas (MHPSA) (Health Resources & Services Administration, 2023) data was included to adjust for community mental health care access. MHPSA data was included as a binary variable, where each ZCTA is either located in an MHPSA (1) or not (0) (SM Figure 2).

The greenspace-mental health association may vary with rurality (Jiang et al., 2021; Ryan et al., 2023). Rurality was included using Rural-Urban Commuting Area (RUCA) codes at the ZCTA-level. RUCA codes range from 1 to 10. This analysis followed RUCA divisions provided by the U.S. Department of Agriculture (USDA) and operationalized rurality with five classifications, where RUCA code 1 was considered urban, RUCA codes 2–3 were considered suburban, RUCA codes 4–6 were considered micropolitan, RUCA codes 7–9 were considered small towns, and RUCA code 10 was considered rural/isolated (USDA, 2020) (Figure 2).

Age categories were considered to see if the greenspace-mental health association changes with age (Feng & Astell-Burt, 2017a). Three age categories, based on US Census age categories (US Census Bureau, 2020), were created to capture childhood (ages 14 and under), adolescence (ages 15–17), and young adulthood (ages 18–24).

Sex was included, where data were categorized as ED visits among males and ED visits among females to see if sex influences the greenspace-mental health association (Sillman et al., 2022).

2.5. Variable Importance

Machine learning was employed to quantify variable importance. Variable importance was determined using the generalized linear model (GLM) elastic net regression (GLMNET) function from the "caret" package in RStudio version 2022.07.1 (RStudio Team, 2022). GLMNET models were run with a Poisson distribution and included greenspace area per person, distance to nearest greenspace, and the perimeter: area ratio; the tune Length was set

10.1029/2023GH000959

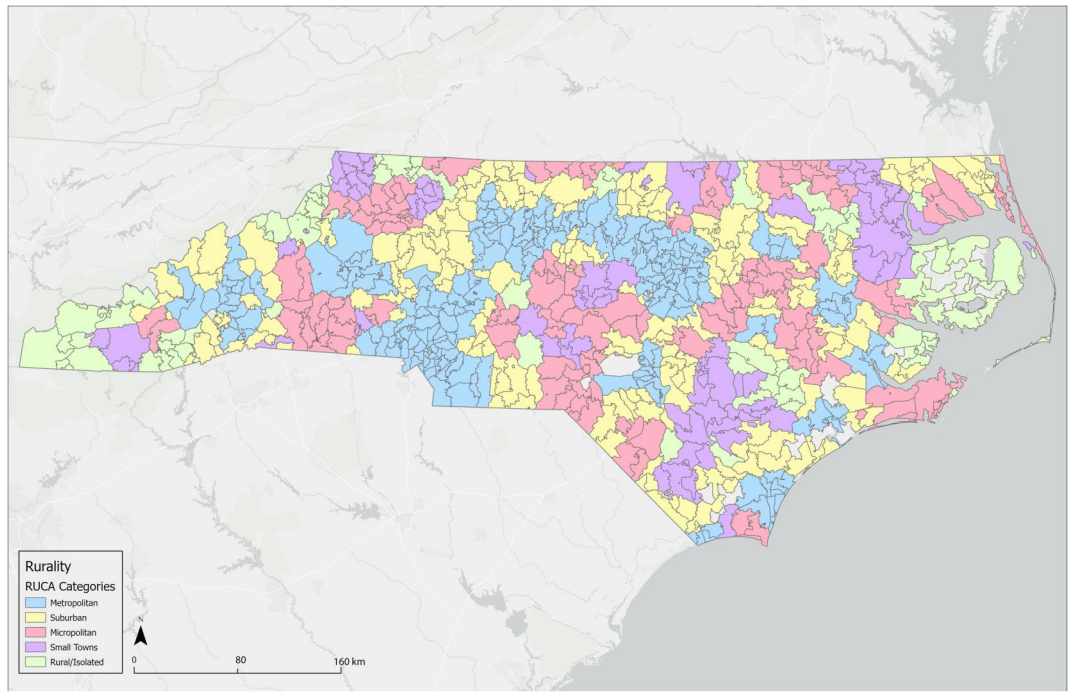

Figure 2. Map indicating the spatial distribution of urban, suburban, micropolitan, small towns, and rural/isolated Zip Code Tabulation Areas. Rurality designations were determined using U.S. Department of Agriculture Rural-Urban Commuting Area codes.

to three as there were three independent variables. Figure S4 in Supporting Information S1 depicts GLMNET results.

2.6. Statistical Analysis

This analysis employed GLMs with a Poisson distribution to analyze the association between community-level mental health prevalence (i.e., total cases per ZCTA, 2016–2019) and greenspace quantity, quality, and accessibility in North Carolina. Stratified analyses were employed to investigate the presence of effect modification by (a) Rurality, (b) Age, and (c) Sex.

GLMs were run to assess if greenspace is associated with community-level mental health outcomes among individuals aged 24 and younger. All five greenspace metrics were considered in the state-wide analysis, and one model was run for each mental health outcome, producing five total models. Models were run such that communities with poor or moderate greenspace quantity, quality and accessibility were compared to those with high greenspace quantity, quality, and accessibility (reference) (Table 1), so as to assess the changing prevalence of mental health outcomes at the community level. High, moderate, and low greenspace metrics were determined by creating tertiles. Due to multicollinearity, percent greenspace was removed from these models in favor of greenspace per person. The Google review-based quality metrics were included in the state-wide analysis but excluded from effect modification analyses as the availability of Google review data was skewed to urban areas.

Stratified GLMs were run to investigate the effect modification of rurality. Age and sex-stratified models were included as a supplemental analysis. Models were run for each rurality designation and each mental health outcome (30 models); each age group and each mental health outcome (18 models); and each sex and mental health outcome (12 models). For the stratified effect-modification analyses, Average Google review and Nearest Google review were removed in favor of the PAR metric, as it is a more standardized measure of greenspace quality.

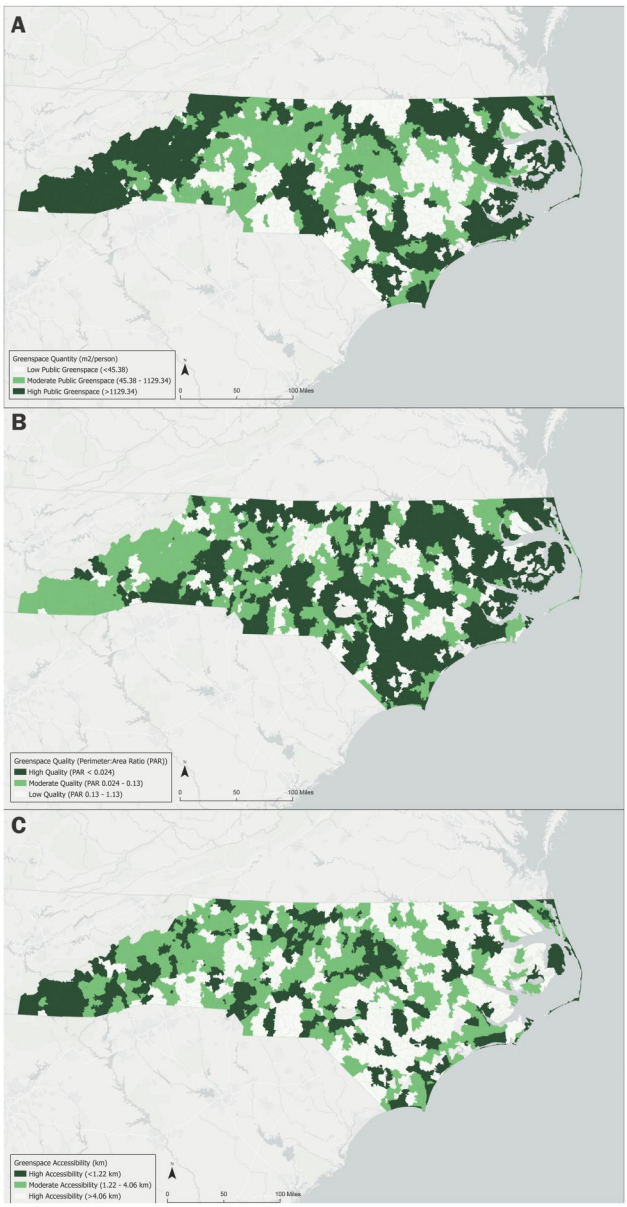

Figure 3. Distribution of greenspace quantity, quality and accessibility. Greenspace metrics are displayed in tertiles.

All GLMs were adjusted for race, income, population, and MHPSA designation. All greenspace metrics and the ICE index metrics were included in the GLMs as tertiles to improve interpretation. MHPSA data was included as a binary, and the population was included as a continuous variable.

Multicollinearity was considered by calculating the Variance Inflation Factor to identify the best model (VIF < 2) (Craney & Surles, 2002; James et al., 2013). The percent greenspace metric was removed for violating the assumption of independence. Models considering all greenspace metrics and sociodemographic factors had the lowest AIC values (Bozdogan, 1987).

3. Results

3.1. Demographic Summary

Table 2 summarizes the demographic characteristics for all ED visits and for each mental health-related ED visit. Overall, there were 5,357,703 total ED visits. ED visits for any mental health concern were highest among females (51.5%–67.7%), white individuals (60.7%–69.6%), and young adults aged 18–24 (48%–92.2%). The most prevalent mental health outcome was substance use disorder followed by anxiety and depression. SM Table 2 reports mental health prevalence by rurality.

3.2. Greenspace Metric Distribution

Throughout North Carolina, greenspace quantity is highest in the western and eastern regions of the state (Figure 3). Southwestern NC and the urban centers of Charlotte, Durham, and Greensboro have the best community-level greenspace access, and many ZCTAs in eastern NC have the worst greenspace access. Greenspace quality, operationalized as the perimeter: area ratio, is the best in eastern NC (smaller PAR values) and worst in western NC (higher PAR values).

3.3. Generalized Linear Models

Table 3 reports state-wide GLM results; all results are reported as prevalence rate ratios (PRRs), indicating the prevalence of each mental health outcome with relation to the variables of interest, compared to the reference group (i.e., communities with high greenspace quantities, better greenspace accessibility, high greenspace quality). PRRs are the equivalent of odds ratios for cohort studies (Tamhane et al., 2016). All five greenspace metrics were included in the state-wide analyses. ZCTAs with low or moderate greenspace quantity (greenspace area/person) were associated with higher PRRs for all mental health outcomes; depression was associated with up to 1.37 (CI: 1.34–1.40) higher prevalence as compared to the ZCTAs with the greatest quantity of public greenspace. Living in ZCTAs with moderate greenspace accessibility were associated with higher prevalence of all mental health outcomes; this increase was highest for anxiety (PRR: 1.28, CI: 1.26–1.30). Moderate greenspace quality was significantly associated with anxiety (PRR: 1.03, CI: 1.01–1.05). ZCTAs with lower reviews of the nearest greenspace were associated with higher PRRs across all mental health outcomes; substance use disorder had the largest PRR values (PRR: 1.33, CI: 1.32–1.34).

3.3.1. Rurality-Stratified

In both urban and suburban ZCTAs, ZCTAs with less greenspace quantity were associated with higher PRRs for all mental health outcomes, as compared to ZCTAs with more greenspace quantity (Table 4). In urban areas, mood disorders saw the greatest increase in prevalence, with mood disorders 19% higher (PRR: 1.19, CI: 1.16–1.21) in ZCTAs with little to no greenspace, and 33% higher (PRR: 1.33, CI: 1.30–1.35) in ZCTAs with moderate

Table 2
Demographic Characteristics of All Emergency Department (ED) Visits and Mental Health-Related ED Visits Among Individuals Ages 24 and Younger Who Visited a North Carolina ED (2016–2019)

	All ED visits *n* (%)	Anxiety *n* (%)	Depression *n* (%)	Mental and behavioral disorder *n* (%)	Mood disorder *n* (%)	Substance use disorder *n* (%)
ED visits	5,357,703 (100%)	97,447 (1.82)	86,924 (1.62)	575,536 (10.7)	119,434 (2.23)	350,277 (6.54)
Average age (SD)	12.49 (8.19)	19.02 (3.96)	18.43 (3.78)	19.13 (4.5)	18.56 (3.89)	21.03 (2.54)
Year						
2016	1,378,846 (25.7)	22,864 (23.5)	19,572 (22.5)	124,878 (21.7)	27,280 (22.8)	72,254 (20.6)
2017	1,371,847 (25.6)	24,300 (24.9)	22,512 (25.9)	150,371 (26.1)	30,745 (25.7)	94,530 (27.0)
2018	1,300,575 (24.3)	25,441 (26.1)	22,496 (25.9)	154,648 (26.9)	30,750 (25.7)	95,531 (27.3)
2019	1,306,435 (24.4)	24,842 (25.5)	22,344 (25.7)	145,639 (25.3)	30,659 (25.7)	87,962 (25.1)
Sex						
Male	2,427,180 (45.3)	31,962 (32.8)	28,581 (32.9)	270,723 (47.0)	42,711 (35.8)	169,465 (48.4)
Female	2,922,642 (54.6)	65,359 (67.1)	58,237 (67.7)	303,969 (52.8)	76,583 (66.7)	180,323 (51.5)
Other/unknown	7,881 (0.1)	126 (0.1)	106 (0.1)	58 (0.0)	140 (0.1)	488 (0.2)
Race						
Indigenous American	74,586 (1.5)	1,104 (1.2)	869 (1.0)	7,524 (1.4)	1,693 (1.5)	5,073 (1.5)
Asian/Pacific Islander	46,042 (0.9)	683 (0.7)	677 (0.8)	3,195 (0.6)	881 (0.8)	1,551 (0.5)
Black	1,902,890 (37.3)	21,098 (22.5)	20,305 (24.3)	175,678 (31.7)	29,168 (25.4)	111,377 (33.0)
White	2,556,293 (50.1)	65,187 (69.6)	56,585 (67.7)	338,448 (61.1)	76,668 (66.7)	204,927 (60.7)
Other	523,995 (10.3)	5,538 (5.9)	5,196 (6.2)	29,214 (5.3)	6,568 (5.7)	14,706 (4.4)
Age group						
Under 15	2,796,174 (52.2)	13,196 (13.5)	14,949 (17.2)	84,031 (14.6)	19,948 (16.7)	4,365 (1.2)
15–17	529,510 (9.9)	16,808 (17.2)	20,215 (23.3)	69,161 (12.0)	25,401 (21.3)	22,943 (6.5)
18–24	2,032,019 (37.9)	67,443 (69.2)	51,760 (59.5)	422,344 (73.4)	74,085 (62.0)	322,969 (92.2)

Note. Data is from NC DETECT.

greenspace quantity. Suburban areas indicate that as greenspace quantity decreases, mental health outcome prevalence increases. In suburban ZCTAs, the association with greenspace quantity was most pronounced for substance use disorders, with a 1.35 (CI: 1.28–1.43) higher prevalence of substance use disorders in ZCTAs with no greenspace, compared to those with the highest quantities of greenspace.

In urban, micropolitan, and rural/isolated areas, increasing distance to the nearest greenspace was associated with higher PRRs across all mental health outcomes. For urban and rural/isolated neighborhoods, this association was most pronounced for substance use disorders, with a 1.31 (CI: 1.29–1.32) higher prevalence in urban areas and a 2.38 (CI: 2.19–2.58) higher prevalence in rural/isolated areas. In micropolitan areas, poor and moderate greenspace accessibility were associated with higher PRRs; this association was greatest for substance use disorders, with 47% (CI: 1.43–1.51) higher prevalence of substance use disorders in ZCTAs with the worst greenspace accessibility, compared to those with the best greenspace accessibility (Table 4).

Both small towns and rural/isolated ZCTAs with worse greenspace quality (higher PAR values) were significantly associated with higher PRRs for all mental health outcomes, compared to ZCTAs with better greenspace quality. In small towns, this association was most substantial for substance use disorders, with 1.4 (CI: 1.33–1.47) higher PRR of substance use disorders in ZCTAs with the worst greenspace quality. In rural/isolated ZCTAs, this association was most pronounced for anxiety, with a 1.61 (CI: 1.53–1.82) higher prevalence of anxiety in ZCTAs with worse greenspace quality, as compared to ZCTAs with better greenspace quality (Table 4).

Table 3
State-Wide Generalized Linear Model Results Investigating the Relationship Between Greenspace Quantity, Quality and Accessibility, and Mental Health Outcomes Among Individuals Ages 24 and Under

	Anxiety		Depression		Mood		Mental and behavioral disorders		Substance Use disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Greenspace quantity: area/person										
Low quantity (0–45.38 m^2)	0.91	0.89–0.93	0.89	0.87–0.92	0.93	0.91–0.95	0.89	0.88–0.89	0.84	0.83–0.85
Moderate quantity (45.92–1,129 m^2)	1.29	1.26–1.31	1.37	1.34–1.40	1.36	1.33–1.38	1.27	1.26–1.28	1.21	1.20–1.23
Reference: high quantity (>1,147 m^2)										
Greenspace accessibility: distance										
Moderate accessibility (1.23–4.06 km)	1.28	1.26–1.30	1.21	1.19–1.23	1.2	1.18–1.22	1.22	1.22–1.23	1.21	1.20–1.22
Poor accessibility (4.09–21.6 km)	1	0.98–1.02	0.93	0.91–0.95	0.95	0.93–0.96	1.06	1.05–1.07	1.1	1.08–1.11
Reference high accessibility (0–1.22 km)										
Greenspace quality: perimeter: area ratio										
Moderate quality (0.01–0.035)	1.03	1.01–1.05	1.01	0.99–1.03	0.99	0.97–1.00	0.97	0.97–0.98	1	0.99–1.01
Low quality (0.035–1.13)[a]	0.75	0.73–0.76	0.79	0.78–0.81	0.76	0.74–0.77	0.75	0.75–0.76	0.76	0.75–0.77
Reference: high quality (0–0.01)										
Greenspace quality: near review										
Low quality (0–4.6)	1.17	1.15–1.19	1.19	1.16–1.21	1.18	1.16–1.20	1.25	1.24–1.26	1.33	1.32–1.34
Moderate quality (4.6–4.8)	0.98	0.96–1.00	1.04	1.02–1.07	1.02	1.01–1.04	0.98	0.97–0.99	0.99	0.98–1.00
Reference: high quality (4.8–5)										
Greenspace quality: average review										
Low quality (0–4.05)	1.07	1.06–1.09	1.1	1.08–1.11	1.07	1.05–1.08	1.07	1.06–1.07	1.07	1.06–1.08
Moderate quality (4.06–4.55)	1.23	1.21–1.25	1.21	1.19–1.23	1.23	1.21–1.25	1.2	1.19–1.21	1.26	1.24–1.27
Reference: high quality (4.56–5)										
ICE: Income										
Low income	1.48	1.45–1.50	1.39	1.36–1.42	1.5	1.47–1.52	1.85	1.83–1.86	2.1	2.08–2.13
Mixed income	1.44	1.42–1.47	1.4	1.38–1.43	1.46	1.44–1.48	1.72	1.71–1.73	1.93	1.91–1.94
Reference: high income										
ICE: Race										
Predominately Black	0.81	0.79–0.82	0.88	0.86–0.90	0.96	0.94–0.97	1.05	1.04–1.06	0.97	0.96–0.98
Mixed race	1.08	1.06–1.10	1.13	1.10–1.15	1.16	1.14–1.18	1.19	1.18–1.20	1.13	1.11–1.14
Reference: predominately white										
MHPSA	1.14	1.08–1.20	1.14	1.08–1.20	1.16	1.11–1.22	1.2	1.17–1.23	1.29	1.25–1.34
Observations: 808										

[a]Includes ZCTAs with no public greenspace.

3.3.2. Age and Sex-Stratified

SM Table 3 reports age-stratified GLM results for the entire state of NC. Across all three age groups (14 and under, 15–17, and 18–24), ZCTAs with less public greenspace quantity (greenspace area per person) were significantly associated with higher prevalence of all mental health outcomes, compared to ZCTAs with more greenspace quantity. SM Table 4 reports sex-stratified GLM results for the entire state of NC. No substantial differences in the greenspace-mental health association were noted between males and females. A detailed explanation of age and sex results can be found in Supporting Information S1.

Table 4

Rurality-Stratified Generalized Linear Model Results Investigating the Association Between Greenspace Quantity, Quality, and Accessibility, and Mental Health-Related Emergency Department Visits Among Individuals Ages 24 and Under With Consideration of Urban, Suburban, Micropolitan, Small Towns, and Rural/Isolated Communities in NC (2016–2019)

	Anxiety		Depression		Mood		Mental and behavioral disorders		Substance use disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Urban										
Greenspace quantity: area/person										
Low quantity (0–3.33 m^2)	1.13	1.10–1.15	1.17	1.14–1.19	1.19	1.16–1.21	1.14	1.13–1.15	1.17	1.16–1.18
Moderate quantity (4.49–136.9 m^2)	1.29	1.26–1.32	1.24	1.21–1.27	1.33	1.30–1.35	1.24	1.23–1.25	1.3	1.29–1.32
Reference: high quantity (>137 m^2)										
Greenspace accessibility: distance										
Moderate accessibility (0.56–1.82 km)	1.01	0.99–1.03	0.98	0.96–1.00	0.98	0.97–1.00	1.11	1.11–1.12	1.12	1.11–1.13
TLow accessibility (1.89–10.7 km)	1.15	1.13–1.17	1.08	1.06–1.10	1.09	1.07–1.11	1.28	1.27–1.29	1.31	1.29–1.32
Reference high accessibility (0–0.53 km)										
Greenspace quality: perimeter: area ratio										
Moderate quality (0.025–0.064)	1	0.99–1.02	0.97	0.95–0.99	0.99	0.98–1.01	1.04	1.03–1.04	1.08	1.07–1.09
Low quality (0.066–1.02)	0.8	0.79–0.82	0.77	0.76–0.79	0.77	0.76–0.79	0.82	0.81–0.83	0.83	0.82–0.84
Reference: high quality (0–0.02)										
ICE: Income										
Low income	1.72	1.68–1.76	1.64	1.60–1.68	1.75	1.71–1.78	2.23	2.20–2.25	2.71	2.67–2.75
Mixed income	1.25	1.22–1.28	1.19	1.16–1.22	1.26	1.24–1.29	1.45	1.44–1.47	1.68	1.66–1.70
Reference: high income										
ICE: Race										
Predominantly Black	0.79	0.78–0.81	0.95	0.93–0.98	1	0.98–1.02	1.16	1.15–1.18	1.11	1.10–1.13
Mixed race	0.85	0.83–0.87	0.95	0.92–0.97	0.96	0.94–0.98	0.99	0.98–1.00	0.97	0.96–0.98
Reference: predominantly white										
MHPSA	1.08	1.02–1.14	1.15	1.08–1.22	1.17	1.11–1.23	1.08	1.06–1.11	1.12	1.08–1.16
Observations: 254										
Suburban										
Greenspace quantity: area/person										
Low quantity (0 m^2)	1.28	1.15–1.43	1.23	1.09–1.38	1.27	1.15–1.40	1.29	1.23–1.34	1.35	1.28–1.43
Moderate quantity (0–1,280.6 m^2)	1.01	0.97–1.06	1.05	1.00–1.10	1.06	1.02–1.11	1.21	1.19–1.23	1.22	1.19–1.25
Reference: high quantity (>1,340.8 m^2)										
Greenspace accessibility: distance										
Moderate accessibility (2.52–6.49 km)	0.76	0.73–0.79	0.72	0.69–0.76	0.73	0.70–0.76	0.79	0.78–0.80	0.81	0.79–0.83
Low accessibility (6.56–17.19 km)	0.66	0.63–0.70	0.67	0.63–0.71	0.7	0.66–0.73	0.74	0.73–0.76	0.74	0.72–0.76
Reference: high accessibility (0–2.5 km)										
Greenspace quality: perimeter: area ratio										
Moderate quality (0–0.021)	1.11	1.06–1.15	1.08	1.03–1.12	1.11	1.07–1.15	1.03	1.02–1.05	1.04	1.02–1.06
High quality (0.022–1.13)	0.78	0.70–0.86	0.77	0.69–0.86	0.74	0.67–0.81	0.81	0.78–0.84	0.78	0.75–0.83
Reference: low quality (0)										
ICE: Income										
Low income	1.38	1.31–1.45	1.25	1.18–1.32	1.4	1.33–1.46	1.61	1.57–1.64	1.82	1.77–1.87

Table 4
Continued

	Anxiety		Depression		Mood		Mental and behavioral disorders		Substance use disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Mixed income	1.53	1.46–1.60	1.5	1.43–1.57	1.49	1.43–1.56	1.55	1.52–1.58	1.62	1.58–1.67
Reference: high income										
ICE: Race										
Predominantly Black	0.59	0.56–0.62	0.63	0.60–0.66	0.68	0.65–0.71	0.77	0.76–0.79	0.71	0.69–0.73
Mixed race	0.62	0.59–0.65	0.67	0.64–0.70	0.7	0.67–0.73	0.71	0.70–0.73	0.67	0.65–0.69
Reference: predominantly white										
MHPSA										
Observations: 202										
Micropolitan										
Greenspace quantity: area/person										
Low quantity (0–12.4 m^2)	0.67	0.62–0.73	0.54	0.50–0.60	0.5	0.51–0.59	0.55	0.54–0.57	0.48	0.46–0.50
Moderate quantity (19.1–1,050.7 m^2)	0.98	0.94–1.02	0.89	0.85–0.93	0.9	0.87–0.94	0.92	0.91–0.94	0.88	0.86–0.89
Reference: high quantity (>1,091.7 m^2)										
Greenspace accessibility: distance										
Moderate accessibility (1.78–5.09 km)	1.48	1.43–1.54	1.49	1.43–1.55	1.53	1.48–1.58	1.39	1.37–1.41	1.37	1.34–1.40
Low accessibility (5.09–20.2 km)	1.35	1.28–1.42	1.32	1.25–1.39	1.36	1.30–1.43	1.4	1.37–1.43	1.47	1.43–1.51
Reference high accessibility (0–1.78 km)										
Greenspace quality: perimeter: area ratio										
Moderate quality (0.008–0.025)	0.78	0.75–0.82	0.74	0.71–0.77	0.73	0.70–0.76	0.66	0.65–0.67	0.6	0.59–0.61
Low quality (0.025–0.56)	0.52	0.48–0.57	0.53	0.48–0.58	0.55	0.51–0.60	0.6	0.58–0.62	0.64	0.61–0.67
Reference: high quality (0–0.006)										
ICE: Income										
Low income	1.71	1.63–1.79	1.45	1.38–1.52	1.52	1.46–1.59	1.58	1.55–1.61	1.77	1.73–1.81
Mixed income	1.64	1.57–1.72	1.53	1.46–1.61	1.53	1.47–1.59	1.74	1.71–1.77	1.95	1.91–2.00
Reference: high income										
ICE: Race										
Predominantly Black	0.99	0.95–1.04	0.99	0.94–1.03	1.15	1.10–1.20	1.2	1.18–1.23	1.06	1.04–1.09
Mixed race	1.38	1.32–1.44	1.36	1.30–1.42	1.47	1.42–1.53	1.59	1.56–1.61	1.46	1.43–1.50
Reference: predominantly white										
MHPSA	1.32	1.08–1.63	1.09	0.89–1.35	1.25	1.04–1.53	1.67	1.52–1.84	2.55	2.20–2.97
Observations: 173										
Small town										
Greenspace quantity: area/person										
Low quantity (0–59.87 m^2)	0.9	0.82–1.00	0.91	0.81–1.02	0.93	0.85–1.03	0.92	0.88–0.96	0.96	0.91–1.01
Moderate quantity (62.11–3,120.2 m^2)	0.72	0.67–0.77	0.78	0.72–0.85	0.75	0.70–0.80	0.84	0.82–0.87	0.87	0.84–0.91
Reference: high quantity (>4,560.2 m^2)										
Greenspace accessibility: distance										
Moderate accessibility (2.36–6.07 km)	0.74	0.69–0.80	0.64	0.59–0.70	0.71	0.66–0.76	0.76	0.73–0.78	0.75	0.72–0.78
Low accessibility (6.16–21.03 km)	0.54	0.48–0.59	0.48	0.43–0.54	0.47	0.43–0.52	0.48	0.46–0.50	0.44	0.42–0.47

Table 4
Continued

	Anxiety		Depression		Mood		Mental and behavioral disorders		Substance use disorder	
	PRR	CI	PRR	CI	PRR	CI	PRR	CI	PRR	CI
Reference high accessibility (0–2.34 km)										
Greenspace quality: perimeter: area ratio										
Moderate quality (0.008–0.027)	1	0.93–1.07	0.99	0.92–1.08	0.97	0.91–1.04	1	0.97–1.03	1.03	0.99–1.07
Low quality (0.027–0.23)	1.15	1.04–1.28	1.17	1.05–1.31	1.12	1.02–1.23	1.29	1.24–1.35	1.4	1.33–1.47
Reference: high quality (0–0.007)										
ICE: Income										
Low income	1.25	1.14–1.37	1.27	1.15–1.42	1.4	1.28–1.53	1.34	1.29–1.39	1.38	1.32–1.45
Mixed income	1.61	1.49–1.74	1.53	1.40–1.66	1.68	1.56–1.81	1.67	1.62–1.73	1.72	1.65–1.79
Reference: high income										
ICE: Race										
Predominantly Black	0.97	0.90–1.05	0.85	0.77–0.93	0.85	0.79–0.91	1.13	1.10–1.17	1.2	1.16–1.25
Mixed race	0.79	0.73–0.86	0.64	0.58–0.70	0.67	0.62–0.72	0.7	0.68–0.73	0.65	0.62–0.67
Reference: predominantly white										
MHPSA	0.55	0.42–0.73	0.35	0.26–0.46	0.43	0.34–0.56	0.61	0.54–0.70	0.91	0.75–1.12
Observations: 85										
Rural/Isolated										
Greenspace quantity: area/person										
Low quantity (0–7,774.03 m^2)	0.55	0.46–0.64	0.66	0.56–0.79	0.7	0.59–0.81	0.61	0.57–0.64	0.54	0.50–0.58
Moderate quantity (8,804.1–49,9595.1 m^2)	1.05	0.93–1.19	1.19	1.03–1.36	1.22	1.08–1.39	1.04	0.99–1.09	0.95	0.89–1.00
Reference: high quantity (>59,922.6 m^2)										
Greenspace accessibility: distance										
Moderate accessibility (0.55–3.19 km)	1.77	1.56–2.02	1.77	1.53–2.05	1.71	1.51–1.95	1.71	1.63–1.80	1.81	1.70–1.92
Low accessibility (3.41–21.56 km)	2.09	1.76–2.49	2.09	1.72–2.53	2.16	1.83–2.56	2.28	2.13–2.44	2.38	2.19–2.58
Reference high accessibility (0–0.45 km)										
Greenspace quality: perimeter: area ratio										
Moderate quality (0.01–0.037)	1.11	0.98–1.27	1.05	0.91–1.21	1.05	0.93–1.20	1.17	1.11–1.23	1.21	1.14–1.28
Low quality (0.041–1.1)	1.61	1.43–1.82	1.27	1.11–1.44	1.3	1.16–1.45	1.23	1.18–1.29	1.19	1.12–1.26
Reference: high quality (0–0.01)										
ICE: Income										
Low income	1.3	1.15–1.48	1.18	1.03–1.35	1.19	1.06–1.34	1.13	1.08–1.18	1.12	1.05–1.18
Mixed income	1.25	1.10–1.41	1.04	0.91–1.18	1.08	0.97–1.22	1.4	1.34–1.47	1.54	1.46–1.63
Reference: high income										
ICE: Race										
Predominantly Black	1.10	0.93–1.29	1.14	0.95–1.37	1.25	1.07–1.48	1.23	1.15–1.31	1.22	1.13–1.32
Mixed race	1.82	1.58–2.10	2.21	1.88–2.6	2.4	2.07–2.78	2.17	2.05–2.30	2.38	2.22–2.55
Reference: predominantly white										
MHPSA										
Observations: 94										

Note. Ruralities were determined using USDA Rural Urban Commuting Area (RUCA) Codes.

4. Discussion

This exploratory study investigated the association between three distinct greenspace metrics: greenspace quantity, quality, and accessibility, and population-level mental health outcomes among children, adolescents, and young adults in North Carolina. Most greenspace-mental health research among children, adolescents, and young adults has focused on behavioral and attention problems. Less focus has been directed at additional mental health outcomes (Vanaken & Danckaerts, 2018); papers report conflicting findings, especially for young adults and adolescents (Mueller et al., 2023; Vanaken & Danckaerts, 2018; Zhang et al., 2020). Most mental disorders develop between the ages of 14 and 24 (American Psychiatric Association, 2023), stressing the need for a better understanding of potential community-based mental health interventions like greenspace for this population. Our analysis found that higher greenspace quantity was associated with a lower prevalence of poor mental health outcomes (i.e., anxiety, depression, mood disorders, substance use disorders and mental and behavioral disorders) in urban and suburban neighborhoods, whereas better greenspace accessibility was associated with a lower prevalence of poor mental health outcomes in urban, micropolitan and rural/isolated areas. Poor mental health prevalence was lower in small towns and rural/isolated communities with higher greenspace quality (operationalized as the PAR). Our findings suggest that greenspace may be protective of a wide suite of mental health outcomes among young people, and this association varies substantially with rurality. These results can help guide targeted, place-based greenspace interventions to lower the prevalence of poor mental health outcomes among young people.

Past research indicates that greenspace quantity is protective for mental health (including neurocognitive development) in urban areas (Bezold et al., 2018; Bijnens et al., 2022; Engemann et al., 2019; Islam et al., 2020; Madzia et al., 2019; P. Wang et al., 2019; R. Wang et al., 2021). Our analysis corroborates these findings, where all five mental health outcomes included in this analysis were more prevalent in urban communities with lower quantities of greenspace. While we cannot derive causal pathways, past studies indicate that higher quantities of greenspace in urban areas can benefit mental health by offering avenues for social cohesion, recreation, and restorative experiences (Liu et al., 2022; R. Wang et al., 2021). Increased greenspace quantity can also help alleviate air pollution and poor mental health attributed to air pollution (Bloemsma et al., 2022). Furthermore, our results contribute to new knowledge that this association remains true in suburban areas. In urban areas, mood disorders were 19% higher in communities with poor greenspace quantities; in suburban areas, substance use disorders were 35% higher in communities with poor greenspace quantities. Untreated mood disorders may be a precursor of adolescent suicide (Runkle, Yadav, et al., 2022); emphasizing the importance of mood disorder interventions among adolescents.

Recent research corroborates our substance use disorder findings; suggesting greenspace may be associated with lower rates of binge drinking and tobacco-use among adolescents and young adults (Wiley et al., 2022) and the general public (Berry et al., 2021; Ryan et al., 2023). Our analysis highlights the protective role of greenspace quantity for young people's mental health in urban and suburban neighborhoods. Higher quantities of greenspace may help reduce rates of binge drinking and tobacco use, as exposure to greenspace can alleviate stress, reduce pain, and encourage informed decision-making (Berry et al., 2021). Findings highlights that higher quantities of public greenspaces may be protective of mental health among young people in both urban and suburban neighborhoods.

Better greenspace accessibility was associated with a lower prevalence of poor mental health outcomes in urban, micropolitan, and rural/isolated neighborhoods. Our results corroborate past research, which found greenspace accessibility was significantly associated with lower mental health burdens among young people in urban communities (Markevych et al., 2017; Zach et al., 2016), and contribute new knowledge that this association is also present in micropolitan and rural communities. For all three ruralities (i.e., urban, micropolitan, rural/isolated), this association was most pronounced for substance use disorders, which were 31% more prevalent in urban neighborhoods with the worst greenspace access, 47% more prevalent in micropolitan neighborhoods with the worst greenspace access, and 138% more prevalence in rural communities with the worst greenspace access. Greenspace accessibility may indicate better opportunities for social cohesion (Dimitrova et al., 2017; Jennings & Bamkole, 2019). Community, family, and social cohesion may be a protective factor against adolescent and young adult substance use (Cleveland et al., 2008; Maclin-Akinyemi et al., 2021; Pei et al., 2020). Furthermore, many of the major outdoor recreation opportunities in North Carolina (e.g., Pisgah National Forest, DuPont State Forest, Cape Hatteras) are in rural and isolated areas. Therefore, our findings may indicate an association between

mental health and economic opportunities afforded by public greenspaces (Bikomeye et al., 2021). Our findings add evidence that greenspace interventions, both quantity and accessibility, may reduce community substance use burdens (Berry et al., 2021; Wiley et al., 2022). Our analysis identified accessibility at the community-level; future research is needed to identify if improved residential accessibility to greenspace at an individual-level can benefit mental health outcomes.

In both small towns and rural and isolated areas, worse greenspace quality, when operationalized as the PAR, was associated with a higher prevalence of poor mental health outcomes. This association was particularly pronounced for substance use disorders, which were 40% more prevalent in small towns with poor greenspace quality, and anxiety disorders, which were 61% more prevalent in rural communities with poor greenspace quality. One of the mechanisms through which greenspace can help alleviate poor mental health is by offering avenues for mindfulness, restorative experiences, and stress reduction (Hedblom et al., 2019; Liu et al., 2022; R. Wang et al., 2021), which can reduce the likelihood of substance use (Berry et al., 2021; Masterton et al., 2022), and can help alleviate symptoms related to anxiety (Song & Lindquist, 2015; Strohmaier et al., 2021). More diverse greenspaces have been reported to provide more restorative experiences, as compared to less biodiverse greenspaces (Wheeler et al., 2015). The PAR is an indicator of biodiversity, which could suggest that in small towns and rural/isolated communities' higher quality (more biodiverse) greenspaces may help alleviate poor mental health outcome prevalence through restorative experiences. As substance use disorders were also significantly associated with greenspace quantity and accessibility, these findings highlight that greenspace interventions; whether in the form of increasing greenspace quantity, accessibility, or quality, may be beneficial for reducing the community substance use disorder burden; these associations are dependent on place. Our findings regarding a higher prevalence of anxiety in rural communities with poor greenspace quality corroborate other analyses, which suggests that one of the main pathways through which greenspaces benefits mental health is via restorative experiences which promote stress reduction (Liu et al., 2022; R. Wang et al., 2021). Our quality metric (PAR) is used as a proxy for habitat fragmentation and biodiversity (Helzer & Jelinski, 1999). Access to more biodiverse greenspaces can aid in promoting overall well being (Carrus et al., 2015; Mavoa et al., 2019). Based on our findings, greenspace interventions in rural areas and small towns should emphasize development of high-quality greenspaces aimed at improving biodiversity (e.g., greenspaces connected to one another, protection of local habitat).

In this exploratory analysis, we hypothesized that place plays an important role in the greenspace-mental health association among young people. Our results suggest that this is true, as the associations between greenspace metrics and mental health prevalence varied among the five ruralities. We further hypothesized that neighborhoods with higher quantities, and better accessibility of greenspace will be associated with a lower prevalence of poor mental health outcomes, particularly in urban and metropolitan neighborhoods. Our results for urban areas support these findings, but our findings in micropolitan areas suggest that the prevalence of poor mental health outcomes is lowest in communities with the least amount of public greenspace. These conflicting findings might highlight the different community structures of semi-urban areas, with micropolitan communities bridging the gap between rural and urban areas (Dabson, 2019). In both small towns and rural/isolated communities mental health prevalence was also lowest in ZCTAs with the least amount of greenspace, which may be because rural areas tend to have higher quantities of private greenspaces (e.g., agricultural fields, home gardens, back yards, etc.) (Ekkel & de Vries, 2017). Past research suggests that private greenspace may also benefit community mental health (Ryan et al., 2023; Verheij et al., 2008), which could help explain our greenspace quantity findings in micropolitan, small town and rural/isolated communities. Our results indicate that with regards to greenspace interventions, micropolitan areas may benefit more from increased accessibility of greenspace, rather than increased greenspace quantity.

4.1. Implications

Our results suggest that greenspace interventions for the mental health of young people vary with place (i.e., urbanity) and greenspace metrics (i.e., quantity, quality, accessibility) (Figure 4). Greenspace quantity interventions may be most beneficial in urban and suburban neighborhoods; greenspace accessibility interventions may benefit mental health in urban, micropolitan, and rural/isolated areas, and greenspace quality interventions aimed at increasing biodiversity should focus on small towns and rural/isolated communities.

Figure 4. Summary of place-based greenspace and mental health findings. Blue boxes indicate a negative association between greenspace and mental health; dark blue boxes indicate the most substantial associations (i.e., largest prevalence rate ratios). Red boxes indicate no association.

Substance use disorders were often associated with the greatest increase in prevalence in communities with poor greenspace accessibility (urban, micropolitan and rural/isolated), quantity (suburban) and quality (small towns). These compelling findings suggest that greenspace interventions, regardless of rurality, may help alleviate the community mental health burden of substance use.

Studies have shown greenspace development is not equitable; such that primarily white and primarily high income communities (Mears & Brindley, 2019) and cities (Rigolon et al., 2018) often have the best access to ample, high quality greenspaces. In the past, greenspace developments in minority neighborhoods have often led to gentrification (Kim & Wu, 2022; Triguero-Mas et al., 2022); with the most affluent benefiting from increased greenspaces; while minority residents and low-income residents face social exclusion and rising housing costs (Cole et al., 2019). Future greenspace interventions need to ensure the development of greenspaces that serve all community members, without leading to displacement and gentrification.

4.2. Strengths and Limitations

Our study has a number of strengths. First, while past studies have relied primarily on self-reported, or parent-reported well-being questionnaires to quantify mental health (Vanaken & Danckaerts, 2018), our analysis employed an objective mental health data set with state-wide coverage, allowing for analysis at the neighborhood scale (i.e., ZCTA). Second, many studies do not consider multiple greenspace metrics (i.e., quality, quantity, accessibility); relying on NDVI to quantify greenspace (Collins et al., 2020; Vanaken & Danckaerts, 2018), or self-reported questionnaires relating to neighborhood greenspace quantity, quality and/or accessibility (Vanaken & Danckaerts, 2018). This analysis considered multiple public greenspace metrics, investigating greenspace quantity, quality, and accessibility, contributing important knowledge for future greenspace-mental health interventions. Third, there is less focus on mental health concerns, such as mood disorders or substance use disorders, with more attention targeted at childhood and adolescent behavior, hyperactivity, and attention (Vanaken & Danckaerts, 2018). This analysis considered a suite of five mental health outcomes (i.e., mood disorders, anxiety disorders, depression disorders, mental and behavioral disorders and substance use disorders). Finally, greenspace-health research is most often conducted in urban settings, consideration of rurality on a spectrum, including suburban, micropolitan and small-town designations, provides location-specific results that can guide future greenspace interventions.

Our study is also limited. Our analysis was conducted at the neighborhood-level, using ZCTAs as our definition of a neighborhood. ZCTA-level analyses may not capture all of the variability within a community and neighborhood scale analyses can result in inflated associations (Kwan, 2021). Furthermore, we did not consider the activity patterns of individuals, and we were unable to account for additional greenspace exposure opportunities outside of the immediate community (i.e., ZCTA); which can lead to exposure misclassification (Kwan, 2021). Third, ED data spans 2016 to 2019, while greenspace data was collected cross-sectionally in 2019 (PAD_US) and 2020 (ParkServe). Fourth, our mental health data, ED administrative data, only captures one cohort of individuals, representing some of the most vulnerable young people in the state (i.e., individuals who may not have mental health care resources outside of the ED) (Schall et al., 2020;

Theriault et al., 2020). With our data set, we may not capture young people who sought mental health care through school counselors, private mental health providers, or those at residential treatment facilities, among others. Fifth, our accessibility metric does not capture accessibility from individual residences; future studies should investigate more accurate accessibility metrics. This analysis was exploratory in nature; given the high number of statistical tests, our results may be subject to Type 1 error. Finally, this analysis did not consider how the greenspace mental health association varies with race, nor did we consider the interaction between greenspace metrics; future studies should consider how race modifies the greenspace mental health association, and the interplay between greenspace metrics.

5. Conclusions

This analysis investigated place-based differences in the association between greenspace metrics (i.e., quantity, quality, and accessibility), and population-level mental health outcomes among young people in North Carolina. Results reveal that greenspace metrics, are associated with population-level mental health benefits, and this association varies with place, such that increasing quantities of greenspace were associated with lower mental health prevalence in urban and suburban communities. We further observe that increasing greenspace accessibility was associated with lower mental health prevalence in urban, micropolitan and rural/isolated communities, and higher quality (i.e., more biodiversity) greenspaces were associated with lower mental health prevalence in small towns and rural/isolated communities. Often, substance use disorders were associated with the greatest increase in prevalence with decreasing greenspace quantity or accessibility. These compelling findings highlight that greenspace interventions, regardless of rurality, may help alleviate the community mental health burden of substance use and mental and behavioral disorders (e.g., anxiety, mood disorders). Place-based results provide important information for targeted mental health interventions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Health data was obtained through an ongoing data use agreement with the North Carolina Department of Health and Human Services (NC Department of Health and Human Services, 2021). Greenspace data was obtained from The Trust for Public Lands—ParkServe (The Trust for Public Land, 2021) and the Protected Area Database of the United States—PADUS (USGS, 2020). Mental Health Professional Shortage Areas—MHPSA data was obtained from the Health Resource and Services Administration (Health Resources & Services Administration, 2023). Rural Urban Commuting Area—RUCA Code data was obtained from the U.S. Department of Agriculture (USDA, 2020). The Index of the Concentration of Extremes (ICE) metrics were calculated using American Community Survey 5-year estimates (US Census, 2018).

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