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Environmental Noise Exposure and Neurodevelopmental and Mental Health Problems in Children: a Systematic Review

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Abstract

Purpose of Review We systematically summarized and evaluated evidence on association between traffic noise exposure and indicators of neurodevelopmental and mental health problems.

Recent Findings Twelve studies on 10 unique populations were reviewed. Different outcomes, mostly measured by the Strength and Difficulties Questionnaire (SDQ) and its subscales, were reported. Overall bias in each study was acceptable, but the quality of evidence for specific outcomes was "low" to "very low," according to the Grading of Recommendations Assessment, Development and Evaluation system.

Summary Data supporting the harmful effect of noise on neurodevelopmental and mental health in children are heterogeneous and limited. Direction of potentially harmful effect was most consistent for road traffic noise and total SDQ score and hyperactivity/inattention. At this point, there is only suggestive evidence that road traffic noise might lead to neurodevelopmental problems in children.

Keywords Traffic noise · SDQ · Behavior · Emotional problems · Development

Introduction

It is estimated that at least one million healthy life years (disability adjusted life years) are lost because of environmental noise in western Europe every year [1••, 2]. There are convincing data to suggest association between traffic noise exposure and various health outcomes in adults, including annoyance, sleep disturbance [1••, 3], cardiovascular disease, and even diabetes [4••]. However, existing evidence for children is still limited. Some studies indicated that children living in noisy environments might be at higher risk, among other outcomes, of elevated blood pressure [5], adiposity [6], and neurobehavioral problems [7]. In terms of burden of disease attributed to environmental noise, cognitive impairment is responsible for 45,000 disability adjusted life years lost on an annual basis [8]. Children have less capacity than adults to anticipate, understand, and cope with stressors, and therefore they are a potentially vulnerable group for non-auditory health effects of noise, especially during sensitive stages of development [9]. However, little is known about the association between noise exposure and children's mental health, and results have been conflicting [10]. A previous review [11•] showed that although there were data supporting an association between noise annoyance, stress, and lower cognitive performance, they were tenuous regarding well-being, hyperactivity, anxiety, and depression. Grounded in previous literature on the subject, a recent study [12] proposed that indirect pathways linking noise to mental ill-health might be intertwined and work together. More

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specifically, traffic noise might not only act as a stressor through increased noise annoyance, but also could constrain restorative experiences in the neighborhood environment, thus inhibit outdoor physical activity and social interactions, and in turn, impinge on neurodevelopmental and mental health problems. Other literature also indicated that some early biological risk factors such as birth weight could modify the observed association between noise and aspects of neurodevelopmental and mental health problems in children [13, 14].

Given the considerable societal costs of mental disorders in children and adolescents [15, 16], gaining deeper understanding of the putative role of environmental noise as a risk factor may serve to expand our perspective on prevention of neurodevelopmental problems in childhood and afterward. Thus, the present study aimed to systematically summarize available data on association between traffic noise exposure and indicators of neurodevelopmental problems and mental health in children.

Materials and Methods

Search Strategy and Study Selection

The systematic review protocol for this study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines [17]. We developed standardized data extraction forms where two reviewers (MJZS and FZS) independently abstracted relevant information. Three databases, including Medline, Scopus, and ISI Web of Science, were systematically searched for available literature on traffic noise exposure and mental ill-health and behavioral problems in children. Searches covered publications published in English until March 15, 2018. We used combination of MeSH and non-MeSH term keywords related to children as population; noise as exposure of interest; and mental ill-health, behavioral, or emotional problems as outcome. Detailed search strategy based on population, exposure, comparison, outcome, and type of study (PECOS) is presented in Supplementary Tables S1–S4. Google Scholar was also searched for gray literature. References of retrieved studies were checked for further relevant publications. Abstracts without full texts, editorials, case reports, reviews, in-vitro, and animal studies were excluded. Studies focused exclusively on occupational noise were also dropped.

Data Extraction

After duplicate removal, titles and abstracts were evaluated according to the study selection criteria by two independent reviewers (M.J.Z.S and F.Z.S). In the case of inconsistency between reviewers, a third reviewer (A.D) assessed the eligibility criteria for the respective study. All relevant data were extracted, including author(s) name, publication date, title, study location, name of study (if available), design, population of interest, age and sex of participants, sample size, type of outcome, exposure and outcome assessment methods, statistical method, estimates of crude and adjusted effect(s), and level of adjustment.

Risk of Bias Assessment

The risk of bias in each study was determined according to the modified checklist previously developed and applied by Dzhambov and Dimitrova [18•]. Briefly, the score comprises 13 items regarding study design and subjects (study design, representativeness of sample, sampling procedure, sample size, response rate of participants), exposure assessment (reported exposure metrics, method of exposure assessment), outcome assessment (valid instrument for outcome assessment, respondent), and analysis and data presentation (adequacy of analysis, adjustment of findings, transparency of effect sizes, and adequacy and clarity of depiction of effect sizes). The maximum attainable score is 42, and we report normalized score for each item and study separately. The normalized score is calculated by dividing attained score in specific domain or study by 42, and then multiplying it by 100.

Quality of Evidence Assessment

The overall quality of evidence was rated according to the Grading of Recommendations Assessment, Development and Evaluation system (GRADE) system [19]. Since we did not perform a quantitative meta-analysis, we used a modified approach similar to the one employed in the World Health Organization (WHO) evidence reviews on noise and health [20••]. We considered sample size of at least 300 as a criterion for adequacy of sample size [19].

Results and Discussion

Study Selection

The literature search retrieved 306 articles, of which, after title and abstract screening, 16 articles were selected for full-text assessment [12–14, 21–28, 29•, 30–33]. Of those, 12 studies fulfilled our selection criteria for entering the systematic review [12–14, 21–24, 28, 29•, 30, 32, 33]. Stansfeld et al. [33] and Crombie et al. [13] used data from the Road Traffic and Aircraft Noise Exposure and Children's Cognition and Health (RANCH) study. They reported several outcomes, some of which were shared in both studies. For outcomes reported in both studies, only the one from Crombie et al. [13] was selected for review. Two studies by Haines et al. [21, 32] focused on the same population consisting of school children in an area with aircraft noise pollution. For outcomes reported in both studies, only the results reported in Haines et al. [21] were considered. However, some of the reported outcomes were different and therefore both studies were used according to the context. Overall, 12 studies on 10 unique datasets were retained in the systematic review. Study selection flowchart is presented in Supplementary Figure 1.

Study Characteristics

In total, 12 studies on 58,458 subjects were selected for this review. Three of selected studies were cohort and the rest were cross-sectional in design. Table 1 presents general characteristics of the selected studies. All [12–14, 21–24, 28, 29•, 30, 32, 33] were performed in European countries. RANCH studies sampled participants from several countries [13, 33]. One study [12] reported results for youth aged 15–25 years, therefore stratified results for those between 15 and 18 years were obtained by re-analyzing the data. All other studies were performed on school-age children (7–11 years).

Different relevant outcomes were reported across studies, mostly measured by the total Strength and Difficulties Questionnaire (SDQ) or its subscale scores, including emotional problems, peer-relation problems, conduct problems, and hyperactivity/inattention [13, 21, 22, 28, 29•, 30]. Only one study reported additional results based on borderline SDQ scores [29•]. However, other instruments, such as the Rating Scale for Disruptive Behavior Disorders (RSDBD) questionnaire [23], the Toulouse Pieron test (in addition to SDQ) [33], the Attention Deficit Disorder Questionnaire [24], and the General Health Questionnaire (GHQ) [12], were also used to measure some aspects or general mental health. In most studies [13, 21–23, 28, 29•, 30, 32], questionnaires were administrated by the parents. Two studies [24, 33] relied on teachers to fill the questionnaires. In two studies, questionnaires were filled by the children [12, 14].

Seven studies [12, 13, 22, 23, 28, 29•, 30] reported results for road traffic noise exposure, one [29•], for railway traffic noise, and five, for aircraft noise [13, 21, 30, 32, 33]. One study on road traffic noise reported results separately for day and nighttime exposure [30]. Another study considered separately indoor and outdoor noise levels [22]. In the study on school-aged children by Dreger et al. [31], effects varied across noise sources. The authors found that exposure to road traffic noise was the main risk factor for incident behavioral problems. Exposure to neighborhood noise was only associated with abnormality in emotional and peer-relation problems subscales in crude models. On the other hand, aircraft and construction noise were not associated with mental health. Contrary to this finding, higher exposure to aircraft noise at school was associated with more hyperactivity symptoms in several other studies [13, 21, 30]. Aircraft noise is generally perceived as more annoying and has higher intensity and variability [34]. Alternatively, children with hyperactivity/inattention problems could be more susceptible to noise [35].

Risk of Bias

Seven studies had good quality score (QS > 80%). Five other studies had moderate QS (51–79%) (Table S5). Among quality domains, all studies scored high on the use of a standard instrument for outcome assessment, sample size, and readily reported effect size estimates. All studies had a sample size of at least 300, which could be regarded as a sufficient [19]. Lack of uniform metrics on reporting of associations and lack of representativeness were the weakest domains in the studies. Regarding 80% of the maximum QS as a cut-point defining good quality studies, the studies had overall good quality only in four domains (transformation, use of standard instrument, sample size, and who filled the questionnaire). Most studies sampled children from a specific part of the city (e.g., near airports), making those samples less likely to be representative of the general population. Lack of representativeness, need for further transformation of outcomes, non-random sampling, and inadequate statistical analysis were respectively among the weakest domains in studies with moderate quality. Response rate, exposure assessment method, and need for further transformation of the results were the weakest domains in studies with good quality respectively.

Exposure Assessment

With regard to exposure assessment methods, one study used parent's self-reported noise annoyance (on a 5-point Likert scale) as a proxy for noise exposure [30]. Five studies used measured noise at schools (schoolyards or classrooms) in the study area [13, 21, 22, 32, 33]. Six other studies considered residential noise exposure [12, 14, 23, 28, 29•, 30]. In three studies, noise exposure was dichotomized based on noise level in two residential areas, and children were allocated in the high- or low-exposure group [21, 24, 32]. One study applied a combination of measurements and modeling [33]. Five studies used modeled noise at participant's residential address [12, 14, 23, 28, 29•]. Noise exposure at home seems to be a better marker of exposure to noise in children than school exposure, because school children spend most of their lifetime (especially night time) at their home [28]. However, only one study simultaneously examined the joint effect of noise exposure at home and school [24].

In two studies on school noise levels, there was no significant association with emotional problems [13, 34]. It seems that duration of noise exposure might be another important factor. Crombie et al. [13] found no significant relationship between road traffic noise at school and hyperactivity/inattention. Students in that study arguably spent roughly half-day at school and the remaining time at home. The difference between school and residential noise can also be considered from another viewpoint. Noise exposure at school captures daytime exposure, while residential exposure covers both day and nighttime periods.

Table 1 General characteristics of selected studies

First author (publication date)	Study name	Location	*N* (age)	Exposure period	Exposure assessment method (exposure source)	Exposure level (metric)	Outcome	Instrument (respondent)
Weyde (2017)	MoBa; cohort	Norway	1934 (8)	Pregnancy; between 3 and 8 years; at age 8	Model (road)	55.8 (L_{den})	Inattention	RSDBD (mother)
Hjortebjerg (2016)	DNBC; cohort	Denmark	46,940 (7)	Birth to 7 years; at age 7	Model (road; rail)	57.9 (L_{den})	Total difficulties; hyperactivity/inattention; conduct problem; peer relationship; emotional symptoms	SDQ (parent)
Forns (2016)	BREATHE; cross-sectional	Spain	2874 (8.55)	At age 8.5	Measurement (road)	38 (dBA)	Total difficulties	SDQ (parent)
Dreger (2015)	GME; cohort	Germany	1185 (9.5)	Between 5.5 and 9.5 years	Parental annoyance (road; aircraft; all at day and night)	Subjective (5-point Likert scale)	Total difficulties	SDQ (parent)
Tiesler (2013)	LISAplus and GINIplus; cross-sectional	Germany	805 (10)	At age of 10 years	Model (road)	48.67 (L_{den})	Total difficulties; hyperactivity/inattention; conduct problem; peer relationship; emotional symptoms	SDQ (parent)
Crombie (2011)[††]	RANCH; cross-sectional	EU countries	1900 (10.55)	At age of 10.5 years	Measurement (road; aircraft)	52 (L_{Aeq})	Total difficulties; hyperactivity; conduct problem; emotional symptoms	SDQ (parent)
Haines (2001)	NA; cross-sectional	UK	451 (9.5)	At age of 9.5 years	Ecological (aircraft)	Below and above 60 dB (L_{Aeq})	Total difficulties; hyperactivity/inattention; conduct problem; peer relationship; emotional symptoms	SDQ (parent)
Stansfeld (2005)[††]	RANCH; cross-sectional	Cross national	1938 (9.5)	At age of 9.5	Model and measurement aircraft	50.25 to 51.25 (L_{Aeq})	Sustained attention; mental health	Toulouse Pieron test; SDQ (teacher)
Ristovska (2004)	NA; cross-sectional	Macedonia	529 (10.5)	At age of 10.5 years	Ecological (all sources at schoolyard)	60 to 65(L_{Aeq})	Anxiety; attention; hyperactivity; social adaptability; opposing behaviors	Attention Deficit Disorder Questionnaire (teacher)
Dzhambov (2017)	NA; cross-sectional	Bulgaria	399 (17.5)	At age of 17.5	Model (road)	L_{den}	Mental health	General Health Questionnaire (GHQ) (student)
Lercher (2002)	NA; cross-sectional	Austria	1403 (9.5)	At age of 9.5 years	Model (highway, rail, local main road)	L_{dn}	Mental health; quality of life	KINDL and index of children's quality of life (children; teacher)

SDQ strengths and difficulties questionnaire, *RSDBD* Rating Scale for Disruptive Behavior Disorders, L_{den} noise level for day-evening-night, L_{dn} noise level for day–night, L_{Aeq} A-weighted equivalent continuous sound pressure level

[††] Both Crombie et al. (2011) and Stansfeld et al. (2005) used data from the RANCH study, but the reported outcomes in the studies are not the same

Studies also differed in terms of noise level and indicator used to express sound pressure level. Mean noise level ranged from 38 dB(A) [22] to 57.9 dB(A) [29•]. Four studies reported L_{den} [12, 23, 28, 29•], one L_{dn} [14] and others, L_{Aeq} [13, 21, 24, 32, 33]. Of the studies that used modeled noise, two calculated it at the most exposed façade of the residential building, one at the living room façade [12], and one study additionally considered noise at the least exposed façade [28]. Results were somewhat different according to the noise modeling approach. Tiesler et al. [28] found children living at homes with higher noise levels at the least exposed façade to have more emotional symptoms. Dreger et al. [30] also found that the relationship between day road traffic noise and total SDQ score was more pronounced for nighttime exposure. Another explanation for weaker association for daytime noise might be the fact that children may pay less attention to noise during the day (e.g., due to being engaged in playing) [31].

Exposure assessment could be regarded as a possible source of heterogeneity between studies. As described in Table 2, noise measurement differs considerably across studies. Using a harmonized methodology in exposure assessment is necessary in future studies. Characteristics such as noise indicator, modeling approach, time of noise measurement, inclusion or exclusion of noise barriers in the model, and similar definition of "day, evening, night" time are among the most important sources of variation in exposure assessment across reviewed studies.

Reported Outcomes

Different outcomes including emotional symptoms [13, 21, 22, 28, 29•, 30, 32], conduct problems [13, 21, 22, 28, 29•, 30, 32], social adaptability [24], hyperactivity/inattention [22, 28, 29•, 32], hyperactivity [13, 21, 24, 30], inattention [23], sustained attention [33], prosocial behaviors [22], opposing behaviors [22], peer-relationship [21, 22, 28, 29•, 30, 32], anxiety [24], and mental health [12, 33] were reported across selected studies.

Total SDQ

Six studies reported total SDQ score [13, 21, 22, 28, 29•, 30], five on road traffic noise [13, 22, 28, 29•, 30], three on aircraft noise [13, 21, 30], and one on railway noise [29•] (Table S6). An increase in both crude and adjusted risk estimates was observed in two studies [29•, 30] on road traffic noise. Three studies on aircraft noise [13, 21, 30] found no significant increase in risk. Exposure to railway noise was associated with higher problems (according to SDQ total score) [29•]. Crude and adjusted risk of abnormal SDQ total score for nighttime road traffic noise was higher than that for daytime noise [30]. Magnitude of effect size in the study using parents' subjective rating as a proxy for exposure was considerably higher than in the other studies [30].

Emotional Symptoms

Out of six studies on emotional symptoms, road traffic, aircraft, and railway noise were considered in five [13, 22, 28, 29•, 30], three [13, 21, 30], and one study [29•], respectively (Table S7). In unadjusted models, two studies [29•, 30] found positive association between road traffic noise and emotional symptoms; in the adjusted models, only one study on nighttime road traffic noise exposure found a significant association [30]. The point estimate in Dreger et al.'s study [30], which used subjective annoyance as a surrogate of noise exposure, was the largest one across studies. Emotional symptoms (in the adjusted model) were lower in those exposed to higher aircraft noise levels in one study [21]. However, the rest of studies on aircraft noise [13, 30] did not show such an effect. In accordance with Haines et al. [21], harmful effect of railway noise was observed only in participants exposed to noise levels lower than 60 dB(A) in comparison with non-exposed subjects. No association was found between emotional symptoms at ages 3–8 years and railway noise above 60 dB(A).

Conduct Problems

An association between exposure to traffic noise and conduct problems (as a subscale in SDQ) was reported in six studies [13, 21, 22, 28, 29•, 30] (Table S8). Five studies considered road traffic noise [13, 22, 28, 29•, 30]. An increase in the risk of conduct problems was observed in four studies in adjusted models [21, 22, 29•, 30], and in two studies in crude models [29•, 30]. The odds of conduct problems for nighttime noise, but not daytime noise, increased significantly [30]. Out of three studies [13, 21, 30] that considered aircraft noise, only one [21] found significant reduction in conduct problems. No evidence supported an association between exposure to railway noise and conduct problems [29•].

Peer-Relation Problems

Associations between road [22, 28, 29•, 30], railway [29•], and aircraft [21, 30] noise and peer-relation problem were reported in five studies [21, 22, 28, 29•, 30] (Table S9). Two studies found a significant effect of road traffic noise in crude models; however, it disappeared in adjusted models [29•, 30]. Among road traffic noise studies that expressed the effect as an odds ratio, the largest effect size was observed in the study of Dreger et al. [30] that had used parental noise annoyance as a surrogate for the noise exposure. In addition, the observed effect for nighttime

Table 2 Detailed description of exposure assessment method across selected studies on association between noise exposure and some aspects of mental health in children

First author	Exposure measurement
Haines (2001)	Ecological exposure assessment based on 16-h daily aircraft noise (Leq A) at school locations from noise contours. L_{Aeq} higher than 63 dBA considered as high-exposure group and schools in area with noise lower than 57 dBA considered as non-exposed groups.
Haines (2001)b	Exposure assessment was relatively similar that described in Haines A; but the exposed group was those in noise counters higher than 66 dBA.
Frones (2016)	Traffic noise measurements took place in the classrooms (three 10-min measurement in each day; two consecutive days). In each school, only one classroom selected and the measurements considered for all school children. All measurements were conducted before students arrive to the class (before 9 A.M.).
Weyde (2017)	Road and rail traffic noise were modeled according to the Nordic prediction model, with CadnaA software at $5 \times 5\text{-m}^2$ grids and 4-m height from surface as L_{den}. Predictions were made at the most exposed façade. Road traffic noise considered as a continuous variable; however, the rail noise used as dichotomous variable (L_{den} lower than 30 dBA or distance from rail and tram more than 700 and 300 m considered as non-exposed).
Ristovska (2004)	Outdoor noise (L_{Aeq}) was measured for schoolyard (8 h in school) and community noise (16 h at cross roads) for schoolyard noise, three consecutive 15-min noise measurement for 4 weeks at spring and autumn was conducted. For community noise, measurements were conducted at cross roads four times (each time 15 min) at spring and autumn.
Tiesler (2013)	Two noise indicators including L_{night} and L_{den} calculated for the road traffic noise at most exposed and least exposed façade based on noise model by CannaA software. Corrections were applied for noise shields in the buildings. The calculation for L_{den} and L_{night} were based on German directives (1 h earlier beginning of the day, evening and night period) compared to European commission.
Hjortebjerg (2016)	Road, rail, and aircraft noise modeled at the most exposed façade of the residential addresses. Road and rail traffic noise modeled according to the Nordic method by SoundPlan software. However, the protective shields only considered for rail noise. Aircraft noise was modeled using DANSIM and INM3 software.
Crombie (2011)	16-h outdoor road and aircraft noise based on L_{Aeq} was modeled admeasured at schoolyards. Other environmental sources of the noise and also rail noise excluded from the study.
Dreger (2015)	Parental noise annoyance was considered as a proxy of noise exposure (5-point Likert scale).
Lercher (2002)	Residential exposure to the highway, rail, and local main road noise was modeled using SoundPlan. The L_{dn} was calculated for each child home. Sound level at non-exposed group home was between 37 and 50 dBA L_{dn}; and 52–71 dBA L_{dn} at exposed group.
Stansfeld (2005)	In Spain, road traffic noise was measured directly in all schools. The aircraft noise was driven from available aircraft noise counters. To take in the account, the role of acute noise events, noise levels during tests were recorded at all locations. In the UK, aircraft noise was driven from available counters and the road traffic noise was calculated from calculation of road traffic noise (CRTN) prediction method. In the Netherlands, both road and aircraft noise were modeled.
Dzhambov (2017)	Road traffic noise was modeled according to the French national method "NMPB-Routes-96" and the standard "XPS 31-133," with LimA software version 5.0 at $10 \times 10\text{-m}^2$ grids and 4-m height from surface for living room façade as L_{den}. Results were based on the 5-dB contours in the range 50–80 dB.

noise was higher than for daytime noise [30]. None of the studies on aircraft noise [21, 30] found a significant association with peer-relation problems in adjusted models.

Hyperactivity/Inattention Problems

Association between traffic noise exposure and hyperactivity/inattention problems (measured by SDQ) was reported by four studies [22, 28, 29•, 32] (Table S10). Three studies [22, 28, 29•] reported results for road traffic noise, and two of those [28, 29•] found an increase in hyperactivity/inattention problems in both crude and adjusted models. However, adjusted effect sizes were slightly lower than crude estimates. None of the studies for railway [29•] and aircraft [32] noise showed a significant increase in the estimates [29•, 32].

Cognitive Function

Inattention, attention, or sustained attention were considered in three studies [23, 24, 33], which used the Attention Deficit Disorder questionnaire [24], the RSDBD [23], and the Toulouse Pieron test [33]. Significant association was found between road traffic noise exposure at the age 8 years, and for cumulative exposure and inattention in children aged 3–8 years in both crude and adjusted models [23]. However, the results in both models for maternal exposure to noise during pregnancy were not significant [23]. No significant association was found for sustained attention and attention in crude models used in two other studies [24, 33].

Mental Health

Mental health and anxiety were assessed by three studies using the GHQ [12], index of children's quality of life [14], and Attention Deficit Disorder questionnaire [24]. Neither found significant association in the total study sample. However, Lercher et al. [14] found that in children with a history of early biological risk (preterm birth, low birth weight), mental health was significantly linked to ambient noise. According to Dzhambov et al. [12], after re-analysis, the total effect of L_{den} on GHQ in those < 18 years was $\beta = 0.778$ (95% CI − 0.124, 1.679; $p = 0.090$).

Interaction, Effect Modification, and Confounding

Early biological risks such as low birth weight and small for gestational age could moderate the relationship between noise exposure and mental health [13, 14]. An increased risk of abnormal mental health was reported only in children who were born preterm or had low birth weight [14]. However, RANCH study data [13] showed no interaction between road or aircraft noise at school and early biological risk for mental health outcomes. On the other hand, the study that excluded those with low birth weight and small gestational age [28] failed to show an association between noise exposure and overall mental health problems. It seems part of this finding might be because of relatively small at-risk population in the study.

Different levels of adjustment across studies made it hard to infer whether some estimates were non-significant because of overadjustment. For example, in the study by Hjortebjerg et al. [29•], in crude models, all estimates for emotional symptoms were significant (in some cases, borderline-significant), but after adjustment, the effect disappeared. However, adjustments in different studies did not follow a similar strategy. Most studies used expert knowledge to adjust their analyses for a priori selection of covariates. Use of directed acyclic graph (DAG) for covariate selection in the models could increase the consistency and hence decrease heterogeneity in findings [35]. On a related point, confounding by air pollution on neurodevelopmental and behavioral problems in children should be considered, given that some air contaminants might influence neurobehavioral functions by entering the brain directly through the olfactory system [36] or by promoting pro-inflammatory cytokines that penetrate the blood-brain barrier [37]. In addition to these biological pathways, air pollution might reduce neighborhood restorative quality through higher annoyance [38], and thereby, inhibit mental health-supporting behaviors in the outdoors [12]. However, the available evidence disentangling the impacts of noise and air pollution on neurodevelopment problems in children is very scarce. In one study [29•], adjustment for NO_x resulted in only minor changes in estimates. Conversely, another study found that the effect of pregnancy noise exposure on inattention was somewhat lowered when including air pollution covariates [23].

Weyde et al. [23] found a statistically significant effect modification by gender and income, but not education, for inattention in those exposed to road traffic noise during the fetal period. The authors observed positive effect modification by education for children of highly educated mothers, and the reverse finding for children of less educated mothers. In that study, there was a significant association only in boys. The results of Weyde et al. [23] stand in contrast to those of Hjortebjerg et al. [29•]. Previous studies found that prenatal stress affects boys and girls differently, and boys might be affected more than girls [39], so this may be an explanation worth investigating.

Sleep problems were associated with significantly higher emotional problems, ($OR_{crude} = 3.07$ (95% CI 1.60–5.90). One study found that after adjustment for sleep problems, the observed association between nighttime noise and emotional problems was attenuated [28]. It also seems there might be a bidirectional association between sleep and emotional problems in children [40].

Plausible Mechanisms

Several mechanistic hypotheses such as stress, sleep disturbance and reduced physical activity, and social cohesion have been proposed to explain observed associations between traffic noise and neurodevelopment problems. Animal and human studies have shown an increased stress response in the case of noise exposure [41]. Exposure to stress during fetal life and early childhood period disturbs cognitive abilities and increases incidence of mental health problem in children [42]. In addition, individuals exposed to noise report annoyance [43], which has been regarded as a likely mediator [44]. Dzhambov et al. [12] illustrated how road traffic noise was associated with higher noise annoyance, lower social cohesion in the neighborhoods, and thus, related to behavioral problems and mental ill-health. Increased annoyance also seemed to act as a constraint on psychologically restorative personenvironment encounters in the neighborhood. Noise annoyance was consequently associated with lower outdoor physical activity and social interactions, and thereby, with mental ill-health. Direct and indirect associations between sleep problems and neurobehavioral functions or behavioral problems including mood and emotion regulation were reported in previous studies [45]. Insufficient sleep reduces brain activities required for maturation of brain. In addition, sleep disturbance might lead to daytime sleepiness and decreased willingness to engage in physical activity [46], thus indirectly diminishing mental health [12]. One study found that after adjustment for sleep problems, the observed association between nighttime noise and emotional problems was attenuated [28]. This suggests that sleep disturbance is a mechanism underlying the effect of noise on neurodevelopmental and mental health problems. Another caveat that should have been considered is that neurodevelopment problems might not just be an outcome, but also a context in which noise impacts on health [44]. That is, there might be a reciprocal association between poor mental health and noise annoyance [47]. Incorrect model specification and ignoring the interplay between mediators might be intertwined could be one of the reasons for the heterogeneous findings in the literature [12].

Conclusions and Future Directions

The global burden of neurodevelopment problems especially mental health problems is continuously rising and inflicts considerable social and economic losses to society [48]. Although prevention of mental and neurodevelopment disorders is among the top priorities for public health policy, in many low- and middle-income countries, it lacks sufficient funding [49], and many people have poor access to mental healthcare [50].

To the best of our knowledge, this is the first systematic review on the association between environmental noise exposure and aspects of neurodevelopment and mental ill-health in children. Our results indicated that evidence on the adverse association of environmental noise exposure on neurodevelopment problems in children is heterogeneous and limited but is suggestive for such an association. Studies considered in this review differed in terms of exposure source, type of exposure assessment, design, participants' age, outcome definition, and statistical methods. According to the GRADE system, the overall quality of evidence for different exposure–outcome scenarios was "low" to "very low," mostly because of high risk of bias, inconsistency of results (i.e., disparate results across studies), and the evidence for some outcomes being based on only one study (Tables S11-S27). Future studies should consider additional noise sources, including indoor, neighborhood, and school sources. Use of more precise exposure assessment methods is also advised. Finally, there is a clear need for exploring pathways linking traffic noise to child mental health, behavior, and neurodevelopmental problems, because understanding underpinning bio-psycho-social processes should enable us to employ specific preventive strategies aiming to promote supportive pathways and disrupt harmful ones.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major Importance

1.•• Basner M, Babisch W, Davis A, Brink M, Clark C, Janssen S, et al. Auditory and non-auditory effects of noise on health. Lancet. 2014;383(9925):1325–32. **This state-of-the-art review summarized current knowledge on auditory and non-auditory health effects, putative mechanisms, mitigation strategies, and knowledge gaps**.
2. World Health Organization, Burden of disease from environmental noise: Quantification of healthy life years lost in Europe, in Burden of disease from environmental noise: Quantification of healthy life years lost in Europe. 2011. p. 126–126.
3. Pirrera S, De Valck E, Cluydts R. Nocturnal road traffic noise: a review on its assessment and consequences on sleep and health. Environ Int. 2010;36(5):492–8.
4.•• Kempen Ev, et al. WHO environmental noise guidelines for the European region: a systematic review on environmental noise and cardiovascular and metabolic effects: a summary. Int J Environ Res Public Health. 2018;15(2):379. **In this systematic review, van Kempen et al. followed a uniform WHO methodology for summarizing available evidence on cardio-metabolic effects of environmental noise, as part of the development of the WHO environmental noise guidelines for the European Region**.
5. Regecová V, Kellerová E. Effects of urban noise pollution on blood pressure and heart rate in preschool children. J Hypertens. 1995;13(4):405–12.
6. Christensen JS, Hjortebjerg D, Raaschou-Nielsen O, Ketzel M, Sørensen TIA, Sørensen M. Pregnancy and childhood exposure to residential traffic noise and overweight at 7 years of age. Environ Int. 2016;94:170–6.
7. van Kempen E, Fischer P, Janssen N, Houthuijs D, van Kamp I, Stansfeld S, et al. Neurobehavioral effects of exposure to traffic-related air pollution and transportation noise in primary schoolchildren. Environ Res. 2012;115:18–25.
8. Clark C, Paunovic K. WHO environmental noise guidelines for the European Region: a systematic review on environmental noise and cognition. Int J Environ Res Public Health. 2018;15(2):285.
9. Matheson M, Stansfeld S, Haines M. The effects of chronic aircraft noise exposure on children's cognition and health: 3 field studies. Noise and Health. 2003;5(19):31–40.

10. Van Kamp, I. and H. Davies. Environmental noise and mental health: five year review and future directions. in Proceedings of the 9th International Congress on Noise as a Public Health Problem. 2008.
11.• Stansfeld S, Clark C. Health effects of noise exposure in children. Current environmental health reports. 2015;2(2):171–8. **Authors narratively reviewed the literature on environmental noise exposure and various health outcomes in children, including mental health, neurodevelopment problems, and stress indicators. Evidence regarding the latter three was somewhat weak**.
12. Dzhambov A, Tilov B, Markevych I, Dimitrova D. Residential road traffic noise and general mental health in youth: the role of noise annoyance, neighborhood restorative quality, physical activity, and social cohesion as potential mediators. Environ Int. 2017;109:1–9.
13. Crombie R, Clark C, Stansfeld SA. Environmental noise exposure, early biological risk and mental health in nine to ten year old children: a cross-sectional field study. Environ Health. 2011;10:39.
14. Lercher P, Evans GW, Meis M, Kofler WW. Ambient neighbourhood noise and children's mental health. Occup Environ Med. 2002;59(6):380–6.
15. Whiteford HA, Degenhardt L, Rehm J, Baxter AJ, Ferrari AJ, Erskine HE, et al. Global burden of disease attributable to mental and substance use disorders: findings from the Global Burden of Disease Study 2010. Lancet. 2013;382(9904):1575–86.
16. Patel V, Flisher AJ, Hetrick S, McGorry P. Mental health of young people: a global public-health challenge. Lancet. 2007;369(9569):1302–13.
17. Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 2009;6(7):e1000097.
18.• Dzhambov AM, Dimitrova DD. Children's blood pressure and its association with road traffic noise exposure—a systematic review with meta-analysis. Environ Res. 2017;152:244–55. **This was the first systematic review with meta-analysis on association between road traffic noise at the residence/school and blood pressure in children. Results were stronger for school noise and suggested that higher noise level increased blood pressure**.
19. Guyatt GH, Oxman AD, Vist GE, Kunz R, Falck-Ytter Y, Alonso-Coello P, et al. GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. BMJ (Clinical research ed.). 2008;336(7650):924–6.
20.•• Nieuwenhuijsen MJ, Ristovska G, Dadvand P. WHO environmental noise guidelines for the European Region: a systematic review on environmental noise and adverse birth outcomes. Int J Environ Res Public Health. 2017;14(10):1252. **In this WHO evidence review, authors found evidence of very low quality for associations between aircraft noise and preterm birth, low birth weight and congenital anomalies, and low quality evidence for an association between road traffic noise and low birth weight, preterm birth and small for gestational age**.
21. Haines MM, Stansfeld SA, Brentnall S, Head J, Berry B, Jiggins M, et al. The West London schools study: the effects of chronic aircraft noise exposure on child health. Psychol Med. 2001;31(8):1385–96.
22. Forns J, Dadvand P, Foraster M, Alvarez-Pedrerol M, Rivas I, López-Vicente M, et al. Traffic-related air pollution, noise at school, and behavioral problems in Barcelona schoolchildren: a cross-sectional study. Environ Health Perspect. 2016;124(4):529–35.
23. Weyde KV, Krog NH, Oftedal B, Magnus P, Øverland S, Stansfeld S, et al. Road traffic noise and children's inattention. Environ Health. 2017;16(1):127.
24. Ristovska G, Gjorgjev D, Pop Jordanova N. Psychosocial effects of community noise: cross sectional study of school children in urban center of Skopje, Macedonia. Croat Med J. 2004;45(4):473–6.
25. Bullinger M, Hygge S, Evans GW, Meis M, Mackensen S. The psychological cost of aircraft noise for children. Zentralbl Hyg Umweltmed. 1999;202(2–4):127–38.
26. Walinder R, et al. Physiological and psychological stress reactions in relation to classroom noise. Scand J Work Environ Health. 2007;33(4):260–6.
27. Haines MM, Stansfeld SA, Job RFS, Berglund B, Head J. A follow-up study of effects of chronic aircraft noise exposure on child stress responses and cognition. Int J Epidemiol. 2001;30(4):839–45.
28. Tiesler CM, Birk M, Thiering E, Kohlböck G, Koletzko S, Bauer CP, et al. Exposure to road traffic noise and children's behavioural problems and sleep disturbance: results from the GINIplus and LISAplus studies. Environ Res. 2013;123:1–8.
29.• Hjortebjerg D, Andersen AM, Christensen JS, Ketzel M, Raaschou-Nielsen O, Sunyer J, et al. Exposure to road traffic noise and behavioral problems in 7-year-old children: a cohort study. Environ Health Perspect. 2016;124(2):228–34. **This population-based cohort study linked road traffic noise exposure from conception to 7 years of age to hyperactivity/inattention symptoms in 7-year-old children**.
30. Dreger S, Meyer N, Fromme H, Bolte G, Study Group of the GME cohort. Environmental noise and incident mental health problems: a prospective cohort study among school children in Germany. Environ Res. 2015;143(Pt A):49–54.
31. Evans GW, Lercher P, Meis M, Ising H, Kofler WW. Community noise exposure and stress in children. J Acoust Soc Am. 2001;109(3):1023–7.
32. Haines MM, Stansfeld SA, Job RF, Berglund B, Head J. Chronic aircraft noise exposure, stress responses, mental health and cognitive performance in school children. Psychol Med. 2001;31(2):265–77.
33. Stansfeld SA, Berglund B, Clark C, Lopez-Barrio I, Fischer P, Öhrström E, et al. Aircraft and road traffic noise and children's cognition and health: a cross-national study. Lancet. 2005;365(9475):1942–9.
34. Ragettli MS, et al. Annoyance from road traffic, trains, airplanes and from total environmental noise levels. Int J Environ Res Public Health. 2015;13(1):90.
35. Fleischer N, Roux AD. Using directed acyclic graphs to guide analyses of neighbourhood health effects: an introduction. J Epidemiol Community Health. 2008;62(9):842–6.
36. Doty RL. The olfactory vector hypothesis of neurodegenerative disease: is it viable? Ann Neurol. 2008;63(1):7–15.
37. Genc S, et al. The adverse effects of air pollution on the nervous system. J Toxicol. 2012, Article ID 782462, p. 23. https://doi.org/10.1155/2012/782462.
38. Von Lindern E, Hartig T, Lercher P. Traffic-related exposures, constrained restoration, and health in the residential context. Health Place. 2016;39:92–100.
39. Hines M, Johnston KJ, Golombok S, Rust J, Stevens M, Golding J, et al. Prenatal stress and gender role behavior in girls and boys: a longitudinal, population study. Horm Behav. 2002;42(2):126–34.
40. Gregory AM, Sadeh A. Sleep, emotional and behavioral difficulties in children and adolescents. Sleep Med Rev. 2012;16(2):129–36.
41. Babisch W, Fromme H, Beyer A, Ising H. Increased catecholamine levels in urine in subjects exposed to road traffic noise: the role of stress hormones in noise research. Environ Int. 2001;26(7):475–81.
42. Barzegar M, Sajjadi FS, Talaei SA, Hamidi G, Salami M. Prenatal exposure to noise stress: anxiety, impaired spatial memory, and deteriorated hippocampal plasticity in postnatal life. Hippocampus. 2015;25(2):187–96.
43. Guski R, Felscher-Suhr U, Schuemer R. The concept of noise annoyance: how international experts see it. J Sound Vib. 1999;223(4):513–27.
44. van Kamp I, et al. Mental health as context rather than health outcome of noise: competing hypotheses regarding the role of sensitivity, perceived soundscapes and restoration. In: Proceedings Internoise; 2013.

45. Sadeh A. Consequences of sleep loss or sleep disruption in children. Sleep Med Clin. 2007;2(3):513–20.
46. Roswall N, Ammitzbøll G, Christensen JS, Raaschou-Nielsen O, Jensen SS, Tjønneland A, et al. Residential exposure to traffic noise and leisure-time sports—a population-based study. Int J Hyg Environ Health. 2017;220(6):1006–13.
47. Schreckenberg, D., et al. The relationship between aircraft sound levels, noise annoyance and mental well-being: an analysis of moderated mediation. in Proceedings of the 12th ICBEN congress on noise as a public health problem, June 18–22. 2017.
48. World Health Organization, Depression and other common mental disorders: global health estimates. 2017.
49. World Health Organization, Mental Health Atlas 2014. Geneva: World Health Organization; 2015. World Health Organization. WHO MiNDbank. http://www.who.int/mental_health/mindbank/en.
50. Wang PS, Aguilar-Gaxiola S, Alonso J, Angermeyer MC, Borges G, Bromet EJ, et al. Use of mental health services for anxiety, mood, and substance disorders in 17 countries in the WHO world mental health surveys. Lancet. 2007;370(9590):841–50.