



# Noise and health in children (in a broader environmental context)

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**Abstract** - Environmental noise is a growing public health problem in a rapidly urbanising world. Foetuses and neonates, children and adolescents can be considered as sensitive to noise because of their continuous physical and cognitive development. Early exposures might have serious effects later on in life and the concept of life-course exposure helps to study the impact of the physical (e.g., acoustic) and social environment on cognitive development and health in young people over time. Life course can be subdivided in different life phases and usually these are based on age and developmental stages. In some life phases people are more susceptible for environmental health effects than in others -so called sensitive periods. It is also possible that health effects of a sensitive period are co- affected by factors during later phases. In that case we speak of a domino effect. Children thus form an important group where environmental quality is concerned and early prevention of diverse environmental effects can have large health benefits also later on in life. Despite of this, children and adolescents have systematically been understudied in the field of environmental epidemiology and the noise field. This paper summarizes the existing knowledge on how children's short and long term health and cognitive development are affected by noise. Some mechanisms are discussed, placing noise in the broader environmental context. Based on this overview we try to convey the message that the noise environments children grow up in have serious long-term effects on their learning and health. Intervention at an early age could benefit society as a whole by enhancing health and education outcomes, thus also addressing the contextual and root causes of social inequalities.

## 1 INTRODUCTION

Environmental noise from transport, industry, recreation, entertainment and appliances is omnipresent and affects our daily life. Noise is hereby defined as unwanted and/or harmful sound, implying that also wanted sound can be harmful (Fink, 2023). Children and adolescents can be considered as a sensitive group for environmental noise. They are not sensitive perse, but they are in a sensitive life phase of continuous mental and physiological development. Early exposures have effects later on in life, but these longitudinal effects are not fully mapped. Most evidence up until recently was based on cross sectional studies, focused on cognitive effects in schoolchildren within a narrow age range and was primarily restricted to aircraft noise. Effects in adults might be different and cannot be generalised one to one to children and adolescents. The mechanisms might also be different in terms of physiology as well as behaviour. The brain is developing until age 25 and children have less well developed coping skills and do not anticipate stress and therefore cannot protect themselves effectively. The influence of a disturbed sleep (sleep stage shifts) on cognition is found to be larger in children and adolescents, but possibly also on the cardiovascular system. Cognitive development and learning is disturbed by the mechanism often referred to as learned helplessness, which affects children's motivation to put effort in the task at hand, while it is noisy. Home exposures, time activities and settings at different ages determine the level of accumulative exposures.

This paper briefly summarizes the current evidence on health effects of environmental noise in children. The evidence is structured along outcomes and life phases where possible.

Also, the findings are placed in a broader environmental context, since there is increasing evidence that a complex interplay between factors at different phases determine effects later on in life. Harmful as well as protective factors play a role. So the detrimental effects of noise might be compensated by beneficial aspects such as the availability of quiet and restorative places – indoor and outdoor – at school and during sports and recreation. Different mechanisms will be outlined and some directions for future action are canvassed at the level of research, governance and consultancy.

## **2 NON-AUDITORY EFFECTS IN CHILDREN**

### **2.1 Introduction**

The WHO environmental noise guideline (WHO, 2018) saw light in November 2018 and summarised the evidence on the health effects of environmental sound exposure at home, weighing the evidence described in seven underlying systematic reviews (Basner and McGuire 2018; Guski et al. 2017; Clark C, Paunovic K. 2018; Van Kempen et al. 2018; Nieuwenhuijsen et al. 2017; Śliwińska-Kowalska and Zaborowski, 2017) using the Cochrane GRADE method<sup>1</sup>. These reviews are based on evidence published between 2000 and December 2014 for annoyance and August 2015 for sleep disturbance, cardiovascular and metabolic effects. Evidence on children was included in the reviews, but not described in all reviews, primarily due to a lack of data. In the guidelines a distinction is made between critical health outcomes, important end emerging health outcomes. For children, sleep disturbance and cognitive impairment feature as critical outcomes. Emotional and conduct disorders such as hyperactivity are rated as important outcomes. Adverse birth outcomes are considered as uncertain. Annoyance in children was not included in the review since very few papers on field studies on noise annoyance in children appeared between 2000-2014. The outcomes for cardiovascular effects of road traffic noise were rated as very low quality. Evidence for aircraft noise was inconsistent and the quality was rated as very low and for other noise sources no evidence was available.

There is very low quality evidence for an association between road traffic noise and both self-reported and motility measured sleep disturbance in children. For other sources, no child specific evidence was reported. Adverse birth outcomes were primarily studied for road traffic noise and reveal evidence of very low quality for birthweight, pre term delivery, small for gestational age and congenital abnormalities. Findings for aircraft noise showed to be inconsistent. No meta-analysis could be performed as a result of too few studies per outcome. The most robust findings were reported for cognitive effects. Evidence rated of moderate quality was available for an association between aircraft noise and reading and oral comprehension, assessed by standardized tests. This relationship is supported by evidence on other measures related to cognition such as performance, and long-term memory. No effect of aircraft noise was found on children's attention and working memory. In summary, the evidence in children is strong and specific for sleep and cognitive outcomes. Effects on conduct disorders and hyperactivity are also prominent and child specific, while results on annoyance and cardiovascular and birth effects are scarce, inconsistent and uncertain.

### **2.2 Evidence since 2014**

All of the above was just up to 2014. Since 2014 several studies and reviews were published, that enhance our knowledge and understanding of the link between environmental noise and health in children. The main effects studied in children include adverse birth outcomes, annoyance, sleep disturbance, endocrine effects, cardiovascular effects, cognitive effects and impacts on mental health and wellbeing. Results of these new studies are briefly summarised below.

#### ***Prenatal effects***

Since 2014 no updated reviews were published on the noise effects of birth outcomes, but two original studies on low birth weight were (Yitshak-Sade et al. 2020)(Smith et al. 2017). Yitshak performed retrospective analysis on 640.659 singleton (one child) births including birthweight as outcome and a range of environmental determinants consisting of PM2.5, temperature, night time noise, natural and built environment exposures, and socioeconomic indices during pregnancy. These were all identified as important predictors of birthweight, even after adjusting for

known individual maternal and neonatal risk factors. They observed lower birthweights in infants born to women with higher temperature exposures during pregnancy, living in areas with less greenness and higher noise levels, living in more walkable areas, and in areas with more of the “low income” population. Looking at the single exposures, night-time noise had the highest weight in predicting lower birthweight. When combining trimestral exposures, the green area as measured by NDVI (Normalized Difference Vegetation Index) was the most highly weighing exposure. Some of the effects found might be due to bias such as selection into specific areas.

Smith et al. (2022) performed secondary analyses on cohort data of singleton births (N= 540 365) with the aim to investigate the relation between exposure to both air- and noise pollution from road traffic and birth weight outcomes. Air pollutant associations were robust to adjustment for road traffic noise. Trends of decreasing birth weight across increasing road traffic noise categories were observed, but were strongly attenuated when adjusted for primary traffic related air pollutants. PM2.5 featured as the most important determinant of low birthweight after adjustment for the other indicators of air pollution.

### **Annoyance**

As concluded by Guski et al. (2017), studies on annoyance in children are rare. In the period since 2014 a few studies addressed annoyance and wellbeing measures in children. Massonnié et al. (2022) looked into the correlational pattern of five responses to noise in the classroom: (1) perceived classroom loudness, (2) hearing difficulties, (3) attention capture, (4) interference, (5) annoyance from noise. They surveyed 112 children between 9 and 11 years old. Results show that children, reporting hearing and switching attention difficulties, experienced more interference and annoyance from noise. Children with attentional problems experienced more activity disturbance, but not more annoyance. Based on these findings a plea is made to make a clear distinction between annoyance and activity disturbance in educational research.

In the Norah study around Frankfurt airport Klätte et al. (2017) looked into the annoyance responses of schoolchildren. Participants were 1234 children between 7-10 years of age. Results show that annoyance presented strong associations with both aircraft- and road traffic noise exposure at school, expressed in the LA,eq.

Minichilli et al. (2018) investigated the relationship between noise perception in school-goers aged 11-17 and noise measurements aimed at evaluating their exposure at school. A questionnaire was administered to 521 children/adolescents in 28 classrooms in eight schools of four cities in Italy, with different environmental characteristics. Using a Likert-type scale, an Annoyance Index (AI) score was generated for each student as well as a classroom median score (MAI). A global noise score (GNS) was assigned to each classroom, based on measurement of six parameters (indoor and outdoor exposure expressed in Leq-int, Leq-ext, insulation of the façade and walls, reverberation time, and speech intelligibility). A higher AI was found in industrialized areas and among younger students. No significant differences in noise judgment were found by gender. The global noise score (GNS) was significantly related to perceived noise and annoyance at classroom level. The results show that noise perception and consequent disturbance are highly correlated with classroom acoustic parameters as mentioned above, and confirm that annoyance represents the most widespread subjective response to noise also in children and adolescents.

### **Sleep**

An update to the WHO Systematic Review and Meta-Analysis by Smith, Cordoza and Basner et al. (2022) added 11 new studies to their meta-analysis from 2017. No additional studies in children were identified. Results do not suggest that the WHO recommendations need revision. Despite this, in their editorial of 2024 the authors (Basner, Smith, 2024) emphasise the importance of undisturbed sleep especially for children. Despite the small number of studies, infants, children, and adolescents are considered as vulnerable groups because of the importance of sleep of sufficient quality and duration for their development.

Weyde et al. (2017) studied the association between nocturnal road traffic noise exposure and children's parental reported sleep duration and sleep problems. Parental report of children's (N=2,665) sleep duration and sleep

problems at age seven were linked to modelled levels of residential night-time road traffic noise. A statistically significant association was observed only in girls for both sleep duration and sleep problems. The findings suggest there is an association between road traffic noise and sleep especially for girls, underlining the importance of protecting children against excessive night-time noise levels.

### ***Cardiovascular effects***

In a study among 2,597 adolescents Wallas (2016) investigated the level of road traffic noise in relation to systolic and diastolic blood pressure (SB and DP). This high quality study confirmed no significant relationship with either type of blood pressure.

### ***Neuroendocrine effects***

Two studies on neuroendocrine effects were published since 2014. Cortisol, glucocorticoid, and their metabolites were the main neuroendocrine outcomes Wallas et al. (2018) and Cantuaria et al. (2018) explored in relation to road-traffic and aircraft noise exposure. Although the Lden indicator provided significant associations between road-traffic noise exposure and cortisol and glucocorticoid metabolites, these were not seen in terms of their total levels in either of the two studies.

### ***Cognition***

In 2022 Thompson et al. published an updated meta-analysis on the impact of environmental noise and cognition, including the studies reviewed by Clark and Panovich for the WHO in 2018. This review covered all age groups, but here we only discuss the effects on children and adolescents. Results of this new review showed moderate quality evidence for an association between aircraft noise and reading and language acquisition in children, and moderate quality evidence against an association between aircraft noise and executive functioning in children. According to the authors more research of high quality using standard measures is needed especially in older teenagers/adolescents. The combined effects of noise- and air pollution should hereby be addressed and geographical spread should be improved. More recently, Gheller et al. (2024) published a review on cognitive effects of noise in children. This systematic review examined the evidence from 26 studies investigating the effects of noise on primary school children's cognitive and academic performance. The reviewed studies show that speech-noise significantly impairs children's verbal working memory, while non-speech/environmental noise showed an effect on academic performance, particularly reading. Other types of environmental noise might on the contrary improve performance especially in children with attention problems. White noise has been shown to effectively improve attention performance especially in children with Attention Deficit Hyperactivity Disorder (ADHD) (Lin, 2022). Studies on the effects on a range of cognitive tasks are rare and cross-sectional and longitudinal studies assessing developmental effects are lacking. In contrast to the WHO guidelines and Thompson et al. and Gheller et al. conclude that the evidence is still too weak to draw firm overall conclusions about the noise effects on children's cognitive and academic abilities.

In 2015 Seabi et al. published a prospective follow-up study on the effects of chronic aircraft noise exposure on children's reading comprehension in South-Africa. It concerns a change study before and after relocation of an airport. The study involved 732 children with a mean age of 11 years at baseline in 2009 and 650 (mean age = 12) and 178 (mean age = 13) at follow-up. Results showed no significant changes across the testing period of one year and indicate the effects measured at baseline were lasting. Next to noise, language spoken at home was a strong predictor of reading comprehension. These findings suggest that exposure to chronic aircraft noise may have a lasting impact on children's reading comprehension functioning and confirm results of studies on cognitive effects around major airports.

Weyde et al. (2017) examined whether road traffic noise was associated with reported inattention symptoms in children, and whether this association was mediated by sleep duration. The study was based on the Norwegian Mother and Child Cohort Study conducted by the Norwegian Institute of Public Health. Parental reports of children's inattention at age 8 were linked to modelled levels of residential road traffic noise at three timeslots:

during pregnancy, at age 5 and age 8. An association with inattention at age 8 years was found for road traffic noise exposure. The association for exposure at age 5, and prenatal was only significant for boys. Results indicate that road traffic noise has a negative impact on children's inattention. No mediation by sleep duration was confirmed.

New studies on the effect of air- and road traffic noise on cognition in school children published after 2014 led to the conclusion that the evidence is still aligned with those from the WHO review (Clark et al., 2020).

A specific field of interest is that of class-room acoustics. In their review in 2023 Murgia et al. concluded that good classroom acoustics is needed to improve speech intelligibility and, therefore, increase children's academic success. Results of this systematic review confirmed the negative effect on intelligibility associated with poor transmission of the speech and poor classroom acoustics caused by long reverberation times and high background noise. More details on acoustic requirements can be found in Loh et al., (2022) and Persson Waye (2021).

### ***Mental health***

In 2020 the WHO review on mental health was updated (Clark et al., 2020). New low-quality evidence shows a harmful effect of road traffic noise on medication use and self-reported measures of depression and anxiety in adults. For children no new evidence was available.

Hjortebjerg et al. (2016) investigated whether residential road traffic noise exposure is associated with behavioural problems in a large cohort of 7-year-old children (n= 46,940 children from the Danish National Birth Cohort). Behavioural problems were assessed by the parent-reported Strengths and Difficulties Questionnaire (SDQ) and road traffic noise (Lden) was modelled at all present and historical addresses. Associations between pregnancy and childhood exposure to noise and behavioural problems were analysed by multinomial or logistic regression and adjusted for potential confounders. A 10-dB increase in average time-weighted road traffic noise exposure from birth to 7 years of age was associated with a modest increase in the SDQ score (in normal and abnormal range), and a 10% increase on the hyperactivity score in the abnormal and borderline range. Exposure to road traffic noise during pregnancy was not associated with child behavioural problems at 7 years of age. It is concluded that road traffic noise in early childhood may be associated with behavioural problems, particularly hyperactivity/inattention symptoms in later phases.

In a study in South Korea among 918 primary and middle school children Lim et al. (2018) looked at the association between road traffic noise and behavioural problems measured with the Child Behaviour Checklist and the role of noise sensitivity and socioeconomic status. Results showed that noise sensitivity was significantly associated with internalizing, externalizing, and total behavioural problems. Noise was positively associated with total behavioural problems. A differential effect was observed for income groups, the association with problem behaviours being higher in the low income group and disappearing in the high-income group. Both income and noise sensitivity should be considered in studying the mental health effects of noise according to the authors.

Newbury et al. (2024) examined the association of exposure to air and noise pollution from pregnancy to age 12 years with three mental health problems assessed at ages 12, 18, and 24 years based in the Avon Longitudinal Study of Parents and Children (ALSPAC) data. Information was available for 14,000 children born between 1991 and 1992. Exposure data were linked on nitrogen dioxide, PM2.5, and noise pollution during pregnancy, childhood (ages 1-9 years), and adolescence (ages 10-12 years). Psychotic experiences, depression, and anxiety were measured at ages 12, 18, and 24 years. Logistic regression analysis was applied while adjusting for confounding at individual, family and area level. Results showed an association between air pollution during pregnancy and incidence of psychosis and depression at a later age. Higher nitrogen dioxide (but not PM2.5) exposure in pregnancy and higher noise pollution in childhood and adolescence were associated with greater odds for anxiety at a later age.

## 2.3 Noise indicators and health effects in children

Terzakis et al. (2022) reviewed the noise and health effects in children literature published in the period between 2000 and 2020 in order to determine which noise indicators from different sources are the best predictors of non-auditory health-effects in children. From the included literature, it was seen that noise exposure, assessed by energetic indicators, has significant associations with psychophysiological, cognitive developmental, mental health and sleep effects. Percentile and event-based indicators provided significant associations to cognitive performance tasks and well-being dimension aspects. Since most studies are based on energy based noise indicators (83%) and only 17% used percentile or event based indicators these findings can be considered as highly explorative at this stage but worthwhile expanding on. The patterns seems to clearly distinguish between instantaneous effects during task performance and interference versus long-term health effects and cognition.

## 3 MECHANISMS

As stated above, the mechanisms underlying the health effects of environmental noise on children might not necessarily be similar to those in adults. The most prevailing model applied to noise and health is a **stress based** framework. Figure 1 is a simple representation of such a cognitive stimulus response model, based on a publication of the Netherlands Health Council and an accompanying paper by Passchier-Vermeer and Passchier in 2000. The model assumes that most effects are a consequence of the appraisal of sound as noise. It is generally assumed that stress responses play an important role in the process by which environmental noise leads to health effects. However, sound can also directly lead to physiological responses. Noise exposure has been shown, as described above, to be associated with annoyance, sleep and activity disturbance and stress responses. These effects are at the base of so called instantaneous bodily effects such as blood pressure increases and increased secretion of cortisol, responses considered as risk factors for cardiovascular diseases and mental pathology. Responses are partly dependent on the noise characteristics (frequency, intensity, duration and meaning) and partly on so called non-acoustical aspects such as context, attitude towards the source, expectations, fear, noise sensitivity, and coping strategies (all to be grouped under hereditary and acquired characteristics in the model shown). The model suggests that only unwanted sound is harmful, but our bodies respond to both wanted and unwanted sound. Noise can thus be better defined as 'unwanted and/or harmful sound' as proposed by Fink (2023) and adopted by the International Commission on Biological Effects of Noise (ICBEN) in 2023.

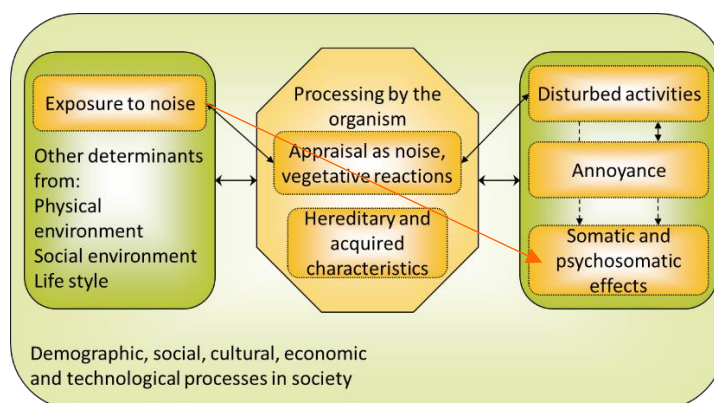


Figure 1: Conceptual framework noise and health (adapted from Passchier-Vermeer and Passchier, 2000 with permission) red arrow added

Although the physiological part of the model is also tenable for children, it is highly questionable whether the pathways especially in young children run via these cognitive processes. Also, children have fewer possibilities for controlling noise/ a less developed coping repertoire. Emotional reaction (angry and sad) but also bodily reactions, symptoms, coping behaviour and wellbeing are important elements in child responses. Research in preschool children has for example shown that more bodily reaction and more perception of a threat is associated with more coping efforts in general (Persson Waye, van Kamp 2013). Compared to adults, young children seem to have a tendency to describe reaction to noise in a somatic way: they literally feel the noise in their body, especially in the head, heart and tummy. At the same time, even at a very young age (3-5) children are capable of responding to questions about their response, feelings and ways they cope with aversive sounds.

Another important mechanism that might explain the long term effects of early exposure to noise in children is referred to as **learned helplessness**. A recent review of Dohmen et al. (2023) assessed the evidence of the sound environment on cognition and learned helplessness as measured by motivation in children and young adults up to the age of 21. The learned helplessness theory concerns a psychological state that is the result of continually encountered (aversive) events that one can do nothing about (Peterson et al., 2023). The review showed evidence for an association between environmental noise, cognition, and helplessness separately, but not for an interaction effect. In a sample of 90 children aged 44 to 69 months, Maxwell and Evans (2000) tested prereading skills (letter-number-word recognition) and children were rated by their teachers on understanding and use of language. The children were tested before and after sound reducing measures in the classroom. Results showed that children scored better in the quiet condition. Also children in the quieter classrooms were less susceptible than those in the noisy classrooms to induced helplessness.

Noise induced behaviours at a young age might affect other aspects of later life: cognitive functioning and possibly also mental health status. Evans and Cassells (2020) showed in a sample of 196 adolescents aged 17 that spending time in poverty from birth-age-9, affected externalizing symptoms and indicators of learned helplessness behaviour. but this was not found for anxiety and depression. The relations between early childhood poverty and externalizing symptoms plus learned helplessness behaviour are according to the authors, mediated by social and physical risk factors such as violence, substandard housing and crowding.

In the literature sleep and restoration have also been identified as important mechanisms in the relation between environmental noise and health in children. Shan Shu and Hui Ma (2018) investigated the **restorative environmental sounds** based on children's perceptions. In the present experiment, children aged 8–12 (N = 36) were exposed to 32 audio-visual stimuli (2 visual × 16 sound stimuli). The perceived restorative value was assessed using the Perceived Restorative Sounds Scale for Children. Factor analysis (PCA) revealed three restorative qualities for both natural sounds and urban sounds, interpreted as attractiveness, compatibility and coherence. In addition, a hierarchical cluster analysis was conducted to subdivide the sounds into four categories with different restorative qualities in two contexts. Results showed that children's perceived restorative evaluation of sounds were positively correlated with fluctuation strength and sharpness, and negatively correlated with loudness and roughness. Those findings illustrate the restorative potentials of environmental sounds as perceived by children.

In a scoping review of van Kamp et al. (2015) **undisturbed sleep** is described as essential for physiological and psychological health. Children have a special need for uninterrupted sleep for growth and cognitive development. Noise is an environmental factor that affects most children, but the knowledge of how children's health, wellbeing and cognitive development are affected by noise disturbed sleep due to road traffic is still very incomplete. It has been shown that although children are less likely to wake up or react with sleep cycle shifts due to night-time exposure, they might be more likely to react with physiological effects such as blood pressure reactions and related motility during sleep. It is concluded that future studies into the health effect of environmental noise exposure in early life should pay specific attention to the mediating role of sleep related aspects. These should include environmental noise in conjunction with other environmental exposures such as indoor climate and exposure to sounds and light from electronic devices.

#### 4 ENVIRONMENTAL NOISE IN A BROADER CONTEXT

In several of the reviewed studies it is recommended that future noise studies should focus on early life and life course exposures. The H2020 project Equal-Life (van Kamp et al., 2022) addresses these combined exposures and their longer term effects (social, physical, lifestyle) in children before conception and up to the age of 21 years and in for them relevant settings. Related time activity patterns are needed to define these settings in more detail per age group. The main challenge is to disentangle the effect of single exposures and at the same time combine them. As we saw in some of the more recent studies described above combining the joint effects of noise, air pollution and access to green space is a complex one. Accounting for inequalities in the exposures and access to more beneficial environments and effects should also be considered. The Equal-Life study distinguishes itself by paying ample attention to the role of social factors and their interplay with the physical environment, by its focus

on children and adolescents, and by taking mental health and cognitive development as main outcomes, including non-chemical exposures, such as environmental noise. The ultimate goal is to provide guidance to (local) authorities and urban planners how to develop the best supportive environments for all children. Conceptual frameworks are being developed describing the mechanism (Persson Waye et al., 2024) and the child environment interaction in relation to all exposure aspects, both positive and negative (Gudi-Mindermann et al., 2023).

## 5 CONCLUSIONS AND A WAY AHEAD

Children can be considered as more vulnerable to noise, especially with regards to cognitive development. Children are also more vulnerable because of less well developed coping skills. Moreover childhood and adolescence can be considered as vulnerable period with regards to development and learning but also mental health. Consequentially (pre) schools should be defined as vulnerable places. Effects of noise have been established on birthweight, reading and sleep, wellbeing and quality of life as well as behavioural effects rather than psycho-pathology. Effects on cognition in general, physiological effects, and cardiovascular effects are still inconclusive. Large life-course studies into the combined long-term effects of early exposures, while adjusting for individual determinants are promising. Methods and models are currently being refined to study the long-term and cumulative effects of combined environmental and social exposures early on in life.

This narrative review makes clear that the field is only slowly expanding and evidence is still fragmented for specific age groups, sources and health effects. Large tailored prospective cohorts following children from preconception until adulthood would ideally be needed to get a better understanding on if and how early exposures can lead to long term health effects. From the little that we do know it is clear that cognitive development and sleep are seriously affected by transport noise and that these effects are stronger in children born into lower socio economic families. Combined effects of air- and noise pollution, access to green, crowding and screentime should urgently be examined. The worldwide increasing prevalence of mental issues in children and adolescence especially becoming visible during and after the pandemic asks for particular attention in vulnerable groups. Early prevention could benefit society as a whole by enhancing (mental) health and education outcomes, thus also addressing the contextual and root causes of social inequalities. Preventive action could be sought in awareness raising and stimulating noise protective behaviour, noise regulations specifically aimed at children and adolescents, and/or at settings they frequent. But also at the technical noise mitigating end, in classrooms and recreational areas for children, a lot of health and cognition gain could be achieved.

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## REFERENCES

- Basner Mathias and Sarah McGuire (2018) WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Effects on Sleep *Int. J. Environ. Res. Public Health*, 15(3), 519; doi:10.3390/ijerph15030519
- Basner Mathias, Michael G Smith, (2024) The effects on sleep play a critical role in the long-term health consequences of noise exposure, *Sleep*, Volume 47, Issue 2, February, zsad314, <https://doi.org/10.1093/sleep/zsad314>
- Bradley, J. S., Lay, K., & Norcross, S. G. (2023). Measurements of the sound insulation of a wood frame house exposed to aircraft noise. Institute for Research in Construction. Canada: National Research Council. doi:10.4224/20386147
- Clark C, Crumpler C, Notley AH. (2020) Evidence for Environmental Noise Effects on Health for the United Kingdom Policy Context: A Systematic Review of the Effects of Environmental Noise on Mental Health, Wellbeing, Quality of Life,

- Cancer, Dementia, Birth, Reproductive Outcomes, and Cognition. *Int J Environ Res Public Health*. 2020 Jan 7;17(2):393. doi: 10.3390/ijerph17020393. PMID: 31936110; PMCID: PMC7013411.
- Clark C, Paunovic K. WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Cognition. *International journal of environmental research and public health*. 2018 Feb 7;15(2):285.
- Dohmen M, Braat-Eggen E, Kemperman A, Hornikx M. (2022) The Effects of Noise on Cognitive Performance and Helplessness in Childhood: A Review. *Int J Environ Res Public Health*. 24;20(1):288. doi: 10.3390/ijerph20010288. PMID: 36612610; PMCID: PMC9819770.
- Evans GW, Cassells RC. Childhood Poverty, Cumulative Risk Exposure, and Mental Health in Emerging Adults. *Clin Psychol Sci*. 2014 May;2(3):287-296. doi: 10.1177/2167702613501496. Epub 2013 Oct 1. PMID: 26609499; PMCID: PMC4655888.
- Fink, Daniel MD (2023) A new definition of noise *The Hearing Journal* 76(11):p 6,7, | DOI: 10.1097/01.HJ.0000995260.15519.9e
- Fink, D., A new definition of noise: noise is unwanted and/or harmful sound. Noise is the new 'secondhand smoke'. Vol. 39. 2019. 050002.
- Gudi-Mindermann, Helen, Maddie White, Jana Roczen, Natalie Riedel, Stefanie Dreger, Gabriele Bolte (2023) Integrating the social environment with an equity perspective into the exposome paradigm: A new conceptual framework of the Social Exposome, *Environmental Research*, Volume 233, , 116485, <https://doi.org/10.1016/j.envres.2023.116485>
- Guski R, Schreckenber D, Schuemer R. (2017) WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Annoyance. *International journal of environmental research and public health*. 2017 Dec 8;14(12):1539
- Kempen van EEMM, Casas M, Pershagen G, Foraster M. (2018) WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Cardiovascular and Metabolic Effects: A Summary. *International journal of environmental research and public health*. 2018 Feb 22;15(2):379.
- Klatte, M., Spijski, J., Mayerl, J., Möhler, U., Lachmann, T., & Bergström, K. (2017). Effects of aircraft noise on reading and quality of life in primary school children in Germany: Results from the NORAH study. *Environment and Behavior*, 49(4), 390–424. <https://doi.org/10.1177/0013916516642580>
- Lim J, Kweon K, Kim HW, Cho SW, Park J, Sim CS. Negative impact of noise and noise sensitivity on mental health in childhood. *Noise Health*. 2018 Sep-Oct;20(96):199-211. doi: 10.4103/nah.NAH\_9\_18. PMID: 30516173; PMCID: PMC6301087.
- Loh, K., Yadav, M., Persson Waye, K., Klatte, M., & Fels, J. (2022). Toward child-appropriate acoustic measurement methods in primary schools and daycare centers. *Frontiers in Built Environment*, 8, 688847.
- Massonnié et al. (2022) J., Frassetto, P., Mareschal, D., & Kirkham, N. Z. (2022). Learning in Noisy Classrooms: Children's Reports of Annoyance and Distraction from Noise are Associated with Individual Differences in Mind-Wandering and Switching skills. *Environment and Behaviour*, 54(1), 58-88. <https://doi.org/10.1177/0013916520950277>
- Maxwell, L. E., & Evans, G. W. (2000). The effects of noise on pre-school children's pre-reading skills. *Journal of Environmental Psychology*, 20(1), 91–97. <https://doi.org/10.1006/jevp.1999.0144>
- Minichilli, F.; Gorini, F.; Ascari, E.; Bianchi, F.; Coi, A.; Fredianelli, L.; Licitra, G.; Manzoli, F.; Mezzasalma, L.; Cori, L. Annoyance judgment and measurements of environmental noise: A focus on Italian secondary schools. *Int. J. Environ. Res. Public Health* 2018, 15, 208. [CrossRef] [PubMed]
- Murgia, Silvia, et al. (2023) Systematic review of literature on speech intelligibility and classroom acoustics in elementary schools. *Language, speech, and hearing services in schools*, 54.1: 322-335.
- Netherlands Health Council, Passchier-Vermeer W, Passchier WF. (2000) Noise exposure and public health. *Environ Health Perspect.*;108 Suppl 1(Suppl 1):123-31. doi: 10.1289/ehp.00108s1123. PMID: 10698728; PMCID: PMC1637786.
- Newbury J.B. et al (2024) Association of early-life exposure to air and noise pollution with youth mental health: findings from the ALSPAC cohort *Lancet Planetary Health*, The 8:S11 25425196

- Nieuwenhuijsen MJ, Ristovska G and Dadvand P. 920170 (2017) WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Adverse Birth Outcomes. *Int. J. Environ. Res. Public Health* 14(10), 1252; doi:10.3390/ijerph14101252
- Persson Waye, K., & Karlberg, J. (2021). Sound quality characteristics of importance for preschool children's perception and wellbeing after an acoustic intervention. *Frontiers in Built Environment*, 7, 688836.
- Peterson, Christopher & Maier, Steven & Seligman, Martin. (2023). Learned Helplessness: A Theory for the Age of Personal Control. 10.1093/oso/9780195044669.001.0001. Persson Waye K, van Kamp I, Dellve L. (2013) Validation of a questionnaire measuring preschool children's reactions to and coping with noise in a repeated measurement design. *BMJ Open*. 28;3(5):e002408. doi: 10.1136/bmjopen-2012-002408. PMID: 23793676; PMCID: PMC3657644.
- Persson Waye, Kerstin, Jesper Löve, Peter Lercher, Angel M. Dzhambov, Maria Klatte, Dirk Schreckenberg, Christin Belke, Larisa Leist, Gordana Ristovska, Sonja Jeram, Katja M. Kanninen, Jenny Selander, Arzu Arat, Thomas Lachmann, Charlotte Clark, Dick Botteldooren, Kim White, Jordi Julvez, Maria Foraster, Jaakko Kaprio, Gabriele Bolte, Achilleas Psyllidis, John Gulliver, Hendriek Boshuizen, Alessandro Bozzon, Janina Fels, Maarten Hornikx, Peter van den Hazel, Miriam Weber, Marco Brambilla, Ella Braat-Eggen, Irene Van Kamp, Natalia Vincens, (2023) Adopting a child perspective for exposome research on mental health and cognitive development - Conceptualisation and opportunities., *Environmental Research*, Volume 239, Part 1, 117279, ISSN 0013-9351, <https://doi.org/10.1016/j.envres.2023.117279>.
- Seabi Joseph, Kate Cockcroft, Paul Goldschagg & Michael Greyling (2015) *Journal of Exposure Science & Environmental Epidemiology* volume 25, pages84–88 (2015)Cite
- Shu, Shan and Hui Ma (2018) The restorative environmental sounds perceived by children *Journal of Environmental Psychology* Volume 60, December 2018, Pages 72-80
- Śliwińska-Kowalska, M and Zaborowski K. (2017) WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Permanent Hearing Loss and Tinnitus. *Int. J. Environ. Res. Public Health* 14(10), 1139; doi:10.3390/ijerph14101139
- Smith MG, Cordoza M, Basner M. (2022) Environmental Noise and Effects on Sleep: *Environ Health* <https://academic.oup.com/sleep/article/47/2/zsad314/7469301> spect; 130(7): 76001 doi: 10.1289/EHP10197
- Smith RB, Fecht D, Gulliver J, Beevers SD, Dajnak D, Blangiardo M, Ghosh RE, Hansell AL, Kelly FJ, Anderson HR, Toledano MB. (2017) Impact of London's road traffic air and noise pollution on birth weight: retrospective population based cohort study.;359;j5299. doi: 10.1136/bmj.j5299. PMID: 29208602; PMCID: PMC5712860.
- Terzakis, M. E., Dohmen, M., van Kamp, I., & Hornikx, M. (2022). Noise Indicators Relating to Non-Auditory Health Effects in Children : A Systematic Literature Review. *International Journal of Environmental Research and Public Health*, 19(23), Article 15633. <https://doi.org/10.3390/ijerph192315633>
- Thompson, Rhiannon, Rachel B. Smith, Yasmin Bou Karim, Chen Shen, Kayleigh Drummond, Chloe Teng, Mireille B. Toledano (2022) Noise pollution and human cognition: An updated systematic review and meta-analysis of recent evidence, *Environment International*, Volume 158, 2022, 106905, ISSN 0160-4120, <https://doi.org/10.1016/j.envint.2021.106905>.
- Weyde KV, Krog NH, Oftedal B, Magnus P, Øverland S, Stansfeld S, Nieuwenhuijsen MJ, Vrijheid M, de Castro Pascual M, Aasvang GM.(2017) Road traffic noise and children's inattention. *Environ Health*. 21;16(1):127. doi: 10.1186/s12940-017-0337-y. PMID: 29162109; PMCID: PMC5698983.
- World Health Organisation. (2018). Environmental noise guideline for the European Region. Denmark: WHO Regional Office for Europe.
- Yitshak-Sade Angela M, Fabian MP, Lane KJ, Hart JE, Schwartz JD, Laden F, James P, Fong KC, Kloog I, Zanobetti A. (2020) Estimating the Combined Effects of Natural and Built Environmental Exposures on Birthweight among Urban Residents in Massachusetts. *Int J Environ Res Public Health*. Nov 27;17(23):8805. doi: 10.3390/ijerph17238805