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Health Effects of Noise Exposure in Children

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Abstract Environmental noise exposure, such as road traffic noise and aircraft noise, is associated with a range of health outcomes in children. Children demonstrate annoyance responses to noise, and noise is also related to lower well-being and stress responses, such as increased levels of adrenaline and noradrenaline. Noise does not cause more serious mental health problems, but there is growing evidence for an association with increased hyperactivity symptoms. Studies also suggest that noise might cause changes in cardiovascular functioning, and there is some limited evidence for an effect on low birth weight. There is robust evidence for an effect of school noise exposure on children's cognitive skills such as reading and memory, as well as on standardised academic test scores. Environmental noise does not usually reach levels that are likely to affect children's hearing; however, increasing use of personal electronic devices may leave some children exposed to harmful levels of noise.

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Introduction

Children are exposed to environmental noise, and a range of different health effects have been described [1]. Yet, there has been less research on the effects of environmental noise in children than in adults. Children have been described as a group vulnerable to the effects of noise [2]. This is because children are exposed to environmental noise and associated pollutants at a time of rapid growth and cognitive development and will perhaps have less developed coping repertoires than adults to deal with environmental noise and less control over noise. This paper examines each of the different health outcomes in which environmental noise has been found to have an impact on children and reports details of illustrative studies in Appendix 1.

Measurement of Noise

External noise exposure metrics are generally used in studies of noise effects on children's health. These measure the average sound pressure over a specific period using dBA as the unit (dBA is the unit of A-weighted sound pressure level in decibels where A-weighted means that the sound pressure levels in various frequency bands across the audible range have been weighted in accordance with differences in human hearing sensitivity at different frequencies) [3, 4]. L_{Aeq16} and L_{day} indicating noise exposure over a 16-h daytime period are the most often used. The daytime period is most often defined 7 am–11 pm; L_{night} indicating night-time noise exposure (11

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pm–7 am); and L_{dn} that is a combination of day-time and night-time noise exposure averaged over 24 h. This includes a 10-dB penalty added to the night-time indicator. The 10-dB penalty reflects people's greater sensitivity to noise exposure at night, and assumes that the effects of noise at night are equivalent to 10 dB more than the same level of exposure during the daytime. In recent studies, noise modelling is used employing geographical information systems, whilst older studies as well as some contemporary studies measure community noise exposure. Direct measurements over brief time periods can be less reliable because noise levels often vary by time of day, and short-term measures may not accurately capture long-term average exposure. More recently, there has been a trend towards measuring exposure to maximum noise levels (e.g. L_{Amax}). It is still not certain whether the 'dose' of overall sound energy, the number of events or the peak sound pressure level of key events is most important for human health effects [3] These are relevant distinctions as, for instance, the number of aircraft overflights and cars on the road are increasing, whilst individual noise emission levels for each event are declining.

'Noise' is usually used to refer to the child's exposure to sound in research on non-auditory effects of noise exposure. This term is used, for both high and low exposure: lower levels in particular may strictly be better described using the term sound. Noise typically implies that the sound exposure is unwanted and that it is a source of environmental stress. We follow this convention in our review.

The Effects of Noise on Low Birth Weight and Prematurity

Low birth weight and prematurity have been the outcomes most examined in relation to environmental noise. Two recent reviews have been published [5, 6]. No consistent associations were found between chronic noise exposure and pregnancy outcomes, but the studies included in both of these reviews varied in study design and measurement of exposure, confounding factors and outcomes. Occupational noise levels assessed in these studies range from above 78 dBA, to 85 dB L_{eq8h}, to above 90 dBA. In the aircraft noise studies, levels are lower with high noise exposure defined as above 65 and 87 dBA. Assessment methods for noise exposure varied using dosimetry, assessments by occupational hygienists, questionnaires and aircraft noise contour maps. The second review found some suggestive evidence of an association between environmental noise and low birth weight but certainly no definitive evidence [5]. Modelled road traffic noise exposure has been linked to low birth weight in a Canadian study of 70,000 administrative birth records [7•]. This association remained after adjustment for air pollution exposure, suggesting that noise has an effect on low birth weight, independent of air pollution. Road traffic is a source of both noise and air pollution both of which have been implicated in health effects. Air pollution is usually measured in terms of gases such as nitrogen dioxide and particulate emissions of different sizes, e.g. $PM_{2.5}$ and PM_{10}. A small significant risk was also found for noise and gestational age but not pre-term birth. There is scope for further studies in this area using standardised measures of noise exposure and birth outcomes.

Endocrine Responses to Noise Exposure

In adults, the mechanism for noise effects on health is thought to be related to the stress hypothesis where noise exposure increases physiological arousal through repeated stimulation of the endocrine system and autonomic nervous system [8]. It is likely that the same mechanism pertains to children as well. Catecholamine and cortisol secretion have been studied as indicators of chronic stress in children exposed to aircraft and road traffic noise. Levels of adrenaline and noradrenaline were raised in both cross-sectional and longitudinal reports from the Munich Study in relation to aircraft noise exposure above 68 dBA and increases in aircraft noise exposure to 62 dBA around the newly opened Munich Airport [9, 10]. This is strong evidence of effects in children because of the longitudinal nature of the study and the increased hormone levels with lengthening duration of noise exposure. However, urinary catecholamines were not raised in the aircraft noise-exposed sample from the West London Schools Study (high noise group >63 dBA, low noise group <57 dBA) [11], albeit a cross-sectional study, and there are insufficient studies to be certain whether noise exposure is related to increased catecholamines. None of these studies have consistently showed a relationship between aircraft noise and urinary cortisol exposure [9–11]. There is undoubtedly a need for further studies in this area where perhaps measures of prolonged raised cortisol might be appropriate.

Blood Pressure Responses to Noise Exposure

There have now been a number of studies investigating the association between road traffic and aircraft noise exposure and blood pressure in children. Whilst it is premature to examine cardiovascular risk in children, studies from adults suggest that repeated elevation of blood pressure in relation to noise exposure might have pathological effects on health in the long term [12•]. Thus, it is appropriate to examine whether noise might be having an effect on blood pressure in children. A recent review [13] found small positive relationships between aircraft noise and blood pressure in children. In this review, road traffic noise studies, although methodologically diverse, showed a stronger relationship with systolic blood pressure. The studies varied in methodology and control for confounding factors. In one study, traffic noise exposure was classified in terms of traffic volume; children whose bedrooms were facing a street with low traffic had the lowest blood pressure readings, whilst the highest readings were found in the group where the children's bedrooms were facing a street with high, or extremely high traffic volume. The difference in blood pressure between the two groups was 1.8 mmHg, (95 % confidence interval (CI) 0.1–3.5, P=0.036) for systolic and 1.0 mmHg (95 % CI −0.4–2.4, P=0.148) for diastolic blood pressure [14]. These sorts of differences are not unlike those seen in other studies of road traffic noise, although in some studies, the differences were as great as 4–5 mmHg [15].

Diastolic blood pressure was related to a 5-dBA increase in L_{den} and L_{night} in 10-year-old children from the GINI-plus, LISA-plus studies adjusting for nitrogen dioxide and three types of particles including PM 2.5 [14]. In adjusted analyses, road traffic noise, ranging from 27–86 dBA, measured in front of the child's bedroom, was independently and positively associated with blood pressure, whereas air pollution was not [16•]. In contrast, another study of 12-year-old children found associations between long-term exposure to nitrogen dioxide and PM 2.5 and diastolic blood pressure but no association with noise exposure, although there were trends with diastolic blood pressure [17]. This could be because traffic noise levels were quite low (45–70.5 dBA L_{den}) with a limited range of exposure in this study. Also, noise measurements made only at the façade of the building may not accurately assess noise exposure in bedrooms at the back of the dwelling. Future studies could adopt a more standardised methodology, but overall, there is increasing evidence of associations between transport noise and blood pressure. Even if these associations are small, the long-term consequences of these blood pressure increases across the lifecourse are unknown and should be studied.

Annoyance

Children may be annoyed by environmental noise in the same way as adults. In the cross-sectional multi-country RANCH study, a curvilinear exposure response relationship was demonstrated between exposure to aircraft noise at school and severe annoyance in children adjusting for confounding factors [18]. The percentage of severely annoyed children increased from about 5.1 % at 50 dB to 12.1 % at 60 dB. Similar associations were found with exposure to aircraft noise at home. In the same study, a linear relationship was found between road traffic noise exposure and annoyance responses. In general, children were less annoyed than their parents at levels above 55 dB, but the shapes of the exposure response relationships were comparable to those in their parents. These associations have also been demonstrated longitudinally in a South African study, where aircraft noise exposure was related to increased levels of annoyance in children over time [19].

Generally, it seems that children are less annoyed by road traffic noise than adults. In a large German study, 7.3 % of 8- to 10-year olds were annoyed by road traffic noise during daytime (yes on a dichotomous scale) compared to 16.4 % of 11- to 14-year olds (collapsed 5-point scale) [20]. This may partly be because of different time activity patterns of children and adults, but also various types of environmental noise may have a different meaning for children and adults. For instance, in this German study, noise from neighbours and noise from family were reported as more annoying for children than road traffic noise. Additionally, children of lower socioeconomic status were more annoyed by road traffic and also those who lived in larger agglomerations of more than 100,000 inhabitants.

Noise-Induced Hearing Loss

Environmental noise does not usually reach levels that are likely to affect hearing in the community. Tinnitus, often associated with hearing loss, has been reported in community surveys of young people associated not only with occupational noise exposure but also with other sources of noise exposure [21]. For young people, the risks to hearing are more likely to result from leisure noise from clubs and rock concerts, and recently, there has been concern over sound levels from personal listening devices. Over the last 20–30 years the number of young people with social noise exposure has tripled to around 19 % [22]. Recently, the sales to young people of personal electronic devices for listening to music have increased enormously. The risks of noise-induced hearing loss from these devices have been compared to the European Noise at Work Regulations recommending an equivalent noise exposure level to 80 dBA for an 8-h working day. The equivalent sound pressure levels of personal electronic devices at maximum volume range from about 80–115 dBA with a mean exposure time ranging from 1 to 14 h a week. On average, it has been estimated that the sound exposure levels from personal electronic devices range from 75 to 85 dBA, so for the majority of personal electronic device users, the risk to hearing is minimal. However, approximately 5–10 % of listeners are considered to be at higher risk due to listening at high level and the long duration of their listening [22]. There may be differences in effects by country, and a much greater prevalence of audiometric notches was demonstrated in the USA than in Germany, although this could also relate to methodological differences between studies [23]. However, it would be fair to say that the risk of hearing loss from these devices is as yet uncertain, and further research will be needed in the future when there is greater experience with these devices. Suffice it to say, there is a need for monitoring hearing over time in young people to check for hearing loss as, although there may be no risk of hearing impairment, if there were a risk it could involve large numbers of young people.

Noise and Sleep Disturbance in Children

Surprisingly, there have been relatively few studies on environmental noise and sleep in children, although children have been identified as a group vulnerable to the effects of sleep disturbance [24]. Prolonged sleep disturbance in children may result in tiredness, difficulties in focussing attention, increased irritability and lowered frustration tolerance [25]. A cross-sectional study of 12-year-old children found a moderate exposure response relationship between road traffic noise exposure at night and sleep quality and problems with sleepiness during the day, but no significant association with difficulties falling asleep [26]. The level of noise exposure at the least exposed façade of a dwelling, perhaps more associated with levels of noise exposure within bedrooms, than noise exposure on the most exposed façade, has been associated with difficulties falling asleep and sleeping problems in a recent community study [27•]. However, night-time aircraft noise exposure did not increase the risk of cognitive impairment beyond the effects of day-time noise exposure in the RANC H and Munich studies [28]. Vulnerable young people may be more at risk of sleep disturbance: ill children in hospital were both more likely to have disturbed sleep before admission, probably related to existing illness and were also found to be woken by noise such as alarms, and attention of hospital staff, potentially disturbing their recovery [29].

Noise and Psychological Health in Children

Quality of Life and Well-being

There have been several studies examining well-being or quality of life in children assessing less severe aspects of psychological disturbance than psychiatric disorder. In Munich, children living in areas exposed to high aircraft noise had lower levels of psychological well-being than children living in quieter environments [9]. The longitudinal data from around Munich showed that after the inauguration of the new airport, the newly noise-exposed communities demonstrated a significant decline in self-reported quality of life, measured on the Kindl scale, after being exposed to the increased aircraft noise for 18 months, compared with a control sample [10]. These studies suggest that noise does not influence children's mental health, though it may affect their stress responses and sense of well-being.

Psychiatric Disorders and Noise Exposure

Anxiety and depression (measured with psychometrically valid scales) were not associated with chronic aircraft noise exposure adjusting for socioeconomic factors in the Schools Health & Environment Study around the Heathrow Airport [30], although road traffic noise at the least exposed façade has been associated with a small increased risk of emotional symptoms on the Strengths and Difficulties Questionnaire (SDQ) [27•, 31].

In a further study of children's health around Heathrow Airport—the West London Schools Study [11]—an association was found between aircraft noise exposure levels and increased scores on the hyperactivity subscale measured by the SDQ. These analyses were revisited in the RANCH Study of 2844, 9- to 10-year-old children living around the Schiphol Airport in the Netherlands, Barajas Airport in Spain and Heathrow Airport in the UK [32]. There were no overall effects of aircraft noise or road traffic noise on children's mental health, measured by the SDQ, but a small association was found with increased hyperactivity subscale scores as in the earlier West London Schools Study [33]. Recent German studies of road traffic noise exposure in 10-year-old children have also shown an association between noise exposure measured as L_{den} at the most exposed façade and increased scores on the hyperactivity subscale of the SDQ [27•], suggesting that this is not an isolated finding. Overall, there is reasonable evidence that noise impairs quality of life in children but does not cause more serious mental health problems. The mechanism by which noise exposure might influence hyperactivity deserves further attention.

Noise and Cognitive Impairment in Children

Studies suggest that the evidence of the effects of noise on children's cognition has grown stronger over recent years, with over 20 studies showing detrimental effects of noise on children's memory and reading outcomes [34]. Recent advances include the use of larger samples, longitudinal studies, the examination of exposure-effect relationships and more thorough assessment of a range of relevant confounding factors [5]. Social deprivation is often associated with high levels of noise exposure; it is also associated with poorer cognitive achievement. Thus, there is considerable potential for confounding in these associations and measures of socioeconomic position must be adjusted for in analyses of noise exposure and cognition and health.

Studies have shown that children exposed to chronic aircraft or road traffic noise at school have poorer reading comprehension and memory than children who are not exposed [11, 30, 35]. A study of 9- to 10-year-old children from rural Alpine areas [36] found that modest levels of ambient community noise (train and road traffic noise above 60 dBA) were associated with poorer memory performance, but not with performance on a test of attention. Several studies have suggested that the effects of noise on children's cognition are not uniform across all cognitive tasks: tasks which involve central processing and language comprehension, such as reading, problem solving and memory appear to be most affected by exposure to noise [37, 38].

Robust evidence for noise effects on children's cognitive performance comes from intervention studies and natural experiments where changes in noise exposure have been accompanied by changes in cognitive performance, such as the Munich Airport study [9, 10, 39]. Prior to the relocation of the airport in Munich, high noise exposure was associated with deficits in long-term memory and reading comprehension in children of 10 years of age. Two years after the airport closed, these cognitive impairments were no longer present, suggesting that effects of noise on cognitive performance may be reversible if noise stops. Furthermore, in a new cohort of noise-exposed children living around the newly opened airport, impairments in memory and reading comprehension developed over the following 2 years. The Munich study remains one of the few longitudinal studies in the field, providing important evidence for a cause-effect relationship between noise exposure and cognitive deficits.

Demonstrating exposure-effect relationships between aircraft noise exposure and children's cognition and learning is important for confirming causal associations between noise and cognition, as well as for identifying thresholds for the effects that can be used by policy makers. The RANCH study found a linear exposure-effect relationship between chronic aircraft noise exposure experienced at school, but not road traffic noise exposure, and impaired reading comprehension and recognition memory, after adjusting for a number of relevant socioeconomic and confounding factors including mother's education, long-standing illness, the extent of classroom insulation against noise, and acute noise during testing [32]. A 5-dB L_{Aeq16} increase in aircraft noise exposure at school was associated with a 2-month delay in reading age in the UK and a 1-month delay in the Netherlands [40]: this association remained after adjustment for aircraft noise annoyance and other cognitive abilities including episodic memory, working memory and attention, as well as air pollution [41•]. The RANCH study suggests that reading comprehension begins to fall below average at aircraft noise exposure greater than 55 dB L_{Aeq16}, but as the association is linear, any reduction in aircraft noise exposure should improve reading comprehension. Long-term exposure to road traffic noise was not associated with cognitive performance. The exception to this was conceptual recall and information recall, which unexpectedly demonstrated better performance in school pupils exposed to higher levels of road traffic noise. Attention and working memory were not consistently influenced by either aircraft noise or road traffic noise.

The development of cognitive abilities such as reading is important not only in terms of educational achievement but also for subsequent life chances and adult health [42]. However, few studies have examined the effects of persistent noise exposure throughout the child's education. The UK subsample of the RANCH study was followed up longitudinally to examine the associations of aircraft noise exposure at primary school on children's reading comprehension at secondary school. This 6-year follow-up of 461 children aged 15 to 16 years, who attended primary and secondary schools around London Heathrow Airport, found that aircraft noise exposure at primary school was associated with a nonsignificant decrease in reading comprehension at follow-up [43]. There was also a weak nonsignificant association between aircraft noise at secondary school and reading comprehension after adjustment for sociodemographic factors. This was a small-scale study, where the small sample size could potentially limit and influence the power to detect significant effects. Further longitudinal lifecourse studies of noise exposure at school and educational outcomes should be conducted.

Studies have also shown effects of noise on standardised achievement tests. Over 40 years ago, Bronzaft and McCarthy [44] demonstrated that children who were taught in classrooms on the noisy side of a school near a railway line had poorer performance on the school achievement tests than those taught in classrooms on the quiet side of the same school in New York. The mean reading age of children in the classrooms on the noisy side of the school was 3 to 4 months behind the children in the low noise-exposed classrooms. A more recent study of national standardised test scores (SATs) carried out around the Heathrow Airport [45], examined test scores for 11,000 11-year-old children in relation to aircraft noise exposure contours for their school. The results showed that there was an exposure-effect relationship between noise exposure and performance on reading and math tests, but that this was influenced by socioeconomic factors. There have been less studies that include assessments of the effects of noise exposure within classrooms as well as external noise exposure, although Shield and Dockrell found associations with both sources of noise at school in relation to national tests for primary school children aged 7–11 years [46]. Older children's performance was most affected by external noise. As the strongest association of test scores was with L_{Amax}, this may be interpreted as individual noise events being important in effects on children's cognition.

The Federal Interagency Committee on Aviation Noise (FICAN) funded a study which assessed the relationship between aircraft noise reduction and standardised test scores in the USA [47, 48]. The study evaluated whether abrupt aircraft noise reduction within classrooms, caused either by airport closure or newly implemented sound insulation, was associated with improvements in test scores, in 35 public schools near three US airports in Illinois and Texas. The study relied on computed noise exposure metrics, which were converted to indoor values, making a comparison with other studies, which use outdoor exposure values, difficult. Overall, this study did find some evidence for effects of aircraft noise reduction and improved standardised test results, although it must be acknowledged that some associations were null and some associations were not in the direction hypothesised. This was a pilot study, and the authors stress that the airports and schools selected for the study may not be representative; that further, larger studies are required; that future studies should utilise airport data for noise exposure assessment; and that outdoor to indoor noise measurements at each school should be considered.

The findings of studies of noise effects on children's cognitive performance suggest that noise may directly affect reading comprehension or that noise effects could be accounted for by other mechanisms including teacher and pupil frustration [38], learned helplessness [49] and impaired attention [38, 50]. Noise might interfere with the interactions between teachers and pupils. In the noisiest schools, teachers may have to stop teaching whilst aircraft fly over, and if this is frequent, it may contribute to interruptions in communication and fatigue in teachers and children and to a reduction of morale and motivation in teachers. Noise also causes annoyance, especially if an individual feels their activities are being disturbed or if it causes difficulties with communication. In some individuals, this annoyance may lead to stress responses. However, at present, there is little evidence to directly support the annoyance pathway as a mechanism for effects on cognition.

Another pathway is that of sleep disturbance caused by noise exposure at home. Where catchment areas for schools are fairly small, there is a strong correlation between home and school aircraft noise exposure [40]. The consequences of sleep disturbance may include poorer well-being resulting in a range of responses: annoyance, irritation, low mood, fatigue and impaired task performance [51]. Overall few studies have examined sleep disturbance as a mediator of noise effects on cognitive performance. A recent analysis of the cross-sectional Munich and RANCH datasets found that self-reported sleep disturbance did not mediate the association of aircraft noise exposure and cognitive impairment in children [28]. Overall, several plausible pathways and mechanisms for the effects of noise on children's cognition have been put forward, but in general evidence for these mechanisms is fairly sparse.

Given the mounting evidence that environmental noise is related to impairment of school performance, the question of what can be done to reduce noise-induced learning impairments becomes salient. One possibility is a reduction of external sound in the classroom through sound insulation. Overall, few studies have examined the influence of noise abatement, via insulation schemes or airport relocation, on children's learning and cognition. Overall, these studies suggest that a reduction of noise exposure can eliminate previously observed cognitive deficits associated with noise but further studies in this area remain a priority.

Further knowledge about exposure-effect relationships would enhance decision-making concerning the design of physical, educational and psychological interventions for children exposed to high levels of noise. Such relationships can be assessed using either individually collected cognitive performance data or via standardised school test data. It may also be productive and informative to derive relationships for a range of additional noise exposure metrics, such as the number of noise events. Recent advances in noise modelling can only further enhance our knowledge about noise effects upon children's learning outcomes.

Conclusion

Environmental noise has multiple effects on children's health. Some of these effects such as raised blood pressure and cognitive impairments may have implications for adult health as well.

In summary, there is sufficient evidence for the effects of environmental noise in children on catecholamine secretion, annoyance, well-being and cognitive effects such as reading comprehension, long-term memory and performance on standardised tests (Table 1). There is scope for further research on hormone responses to noise in children which may link to elevated blood pressure in relation to noise. Findings on elevated blood pressure have been very mixed and further studies with better measures of noise exposure are needed. Similarly, the impact of environmental noise on low birth weight and

Table 1 Noise and children's health: strength of evidence

	No evidence	Limited	Sufficient
Low birth weight/prematurity			
Occupational noise	+		
Environmental noise		+	
Endocrine responses			
Catecholamines			+
Cortisol	+		
Elevated blood pressure		+	
Annoyance			+
Noise induced hearing loss		+	
Sleep disturbance		+	
Well-being		+	
Anxiety and depression	+		
Hyperactivity		+	
Reading comprehension and long-term memory			+
Standardised achievement tests			+

prematurity deserves further investigation because of recent suggestive findings. The repeated finding that aircraft noise is related to hyperactivity symptoms requires some systematic investigation and undoubtedly the prolonged use of personal listening devices on hearing needs to be assessed in longitudinal studies, not least because of the public health implications of almost universal use in young people.

There is need for studies in the future which take a lifecourse perspective partly because noise exposure can have different effects at different developmental stages, and partly, because that allows consideration of the effects of cumulative exposure to pollutants and how these might influence developmental trajectories and health into adult life.

Compliance with Ethics Guidelines

Conflict of Interest Stephen Stansfeld reports personal fees from High Speed 2 Ltd., Arup Engineering, and the World Health Organisation.

Charlotte Clark reports personal fees as an expert panel member of the UK Airport's Commission, personal fees from WHO Europe Community Noise Guideline revisions, and a grant from the Department of Environment, Food and Rural Affairs, UK.

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.

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