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Authors
Clark, Charlotte
Stansfeld, Stephen A

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The Effect of Transportation Noise on Health and Cognitive Development: A Review of Recent Evidence

Charlotte Clark and Stephen A. Stansfeld
Barts & the London School of Medicine
University of London, United Kingdom

Noise from transport is an increasingly prominent feature of the urban environment. Whilst the auditory effects of noise on humans are established, non-auditory effects - the effects of noise exposure on human health, well-being and cognitive development - are less well established. This narrative review evaluates recent studies of aircraft and road traffic noise that have advanced or synthesized knowledge about several aspects of adult and child health and cognition. Studies have demonstrated a moderate effect of transport noise on hypertension, cardiovascular disease and catecholamine secretion: there is also evidence for an effect on psychological symptoms but not for the onset of more serious clinically defined psychiatric disorder. One way noise may affect health is through annoyance: noise causes annoyance responses in both children and adults and annoyance may cause stress-responses and subsequent illness. Another possible mechanism is sleep disturbance: transport noise has been found to disturb sleep in laboratory and field studies, although there is evidence for adaptation to noise exposure. For children effects of aircraft and road traffic noise have been observed for impaired reading comprehension and memory skills: there is equivocal evidence for an association with blood pressure. To date most health effects have been very little researched and studies have yet to examine in detail how noise exposure interacts with other environmental stressors. In conclusion, noise is a main cause of environmental annoyance and it negatively affects the quality of life of a large proportion of the population. In addition, health and cognitive effects, although modest, may be of importance given the number of people increasingly exposed to environmental noise and the chronic nature of exposure.

Exposure to noise in the environment from transport sources is an increasingly prominent feature of the environment. The growing demand for air and road travel means that more people are being exposed to noise, and noise exposure is increasingly being seen as an important environmental public health issue.

The direct effect of sound energy on human hearing is well established and accepted. Exposure to continuous noise of 85-90 dBA (decibels, A-weighted to approximate the typical sensitivity of the human ear) can lead to progressive hearing loss and changes in threshold sensitivities (Kryter, 1985): similar damage can be caused by exposure to a smaller number of noise events, if the sound energy is great (>135 dB Lc_{pk}, Babisch, 2005) (LC_{pk} is a measurement of peak sound pressure level over a specified period). Auditory effects of noise have typically been observed in certain industrial occupations, hence protective legislation requiring hearing protectors to be worn, however, effects are also increasingly being observed due to entertainment noise from amplified music and MP3 players.

In contrast, non-auditory effects of noise on human health are not the direct result of sound energy. Instead, these effects are the result of noise as a general stressor: thus the use of the term noise not sound: noise is unwanted sound. Non-auditory effects of noise include sleep disturbance, mental health, physiological

Correspondence concerning this article should be addressed to Charlotte Clark, Centre for Psychiatry, Barts and the London School of Medicine and Dentistry, University of London, Charterhouse Square, London EC1M 6BQ, U.K. (c.clark@qmul.ac.uk).

function, and annoyance, as well as effects on cognitive outcomes such as speech communication, and cognitive performance (WHO, 2000). These effects of noise are less well established and accepted than auditory effects.

Noise could indirectly result in poor health in several ways. Firstly, acute noise exposure directly causes a number of predictable short-term physiological responses such as increased heart rate, blood pressure, and endocrine outputs. Chronic noise exposure may cause longer-term activation of these responses and subsequent symptoms and illness. Whether acclimation of the physiological response occurs with long-term noise exposure is not certain. Secondly, these physiological responses may be activated by annoyance. Noise 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, and potentially to subsequent symptoms and illness. However, there is little evidence to directly support the annoyance pathway as a mechanism for non-auditory effects. Habituation[1] of behavioral or psychological responses may occur with long-term exposure for certain individuals or for certain types of behavioral responses: however, the reduction of a behavioral or psychological response may not necessarily result in the acclimation of a physiological response.

This narrative review evaluates recent studies of transport noise that have advanced or synthesized the knowledge about several non-auditory effects: namely, hypertension and coronary heart disease, stress hormones, sleep disturbance, mental health, and cognitive development: effects for children and adults are discussed. Recent years have seen several methodological advancements in the field including the use of larger epidemiological community samples; better characterization of noise measurement; and more detailed measures of health. Evidence from longitudinal studies is beginning to emerge and studies have started to examine exposure-effect relationships, to identify thresholds for noise effects on health and cognition which can be used to inform guidelines for noise exposure. There has also been a better assessment of confounding factors: noise exposure and health are often confounded by socioeconomic position, so individuals living in poorer social circumstances are more likely to have poorer health, as well as be exposed to noise. Therefore, measures of socioeconomic position need to be taken into account when examining associations between noise exposure and health. Furthermore, factors that confound physiological health outcomes such as smoking, diet, and activity levels also need to be measured and adjusted for in analyses.

Review of the Evidence

Noise Exposure Assessment

Assessments of noise exposure use established metrics of external noise exposure which indicate the average sound pressure level for a specified period

[1] Habituation is distinguished from acclimation in this paper in the following way. Habituation refers to the lessening of a behavioural or psychological response to noise, with repeated or chronic exposure: e.g. a reduction in sleep disruption or annoyance responses. Acclimation refers to the lessening of a physiological response to noise, with repeated or chronic exposure: e.g. a reduction in cortisol levels.

using dBA as the measurement unit (dBA is the unit of A-weighted sound pressure level 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 hearing sensitivity at different frequencies). Metrics typically employed are L_{Aeq16} and L_{day} which indicate average noise exposure (in dBA units) over a 16 hour daytime period usually 7am-11pm; L_{night} which indicates noise exposure at night (11pm-7am); and L_{dn} which combines the day and night measures to indicate average noise exposure over the 24 hour period, with a 10dB penalty added to the night-time noise measure. These metrics are usually modeled using Geographical Information Systems. Some studies measure noise exposure in the community, which is less reliable if measurements cover short time-periods. Studies have also examined exposure to maximum noise levels (e.g. L_{Amax} - maximum sound pressure in dBA units), as in pathophysiological terms it is not clear whether overall 'dose' of noise exposure is important in determining effects on health or whether peak sound pressure of events or the number of noise events might be important.

Whilst people are often exposed to sounds from more than one source, to date, studies have tended to focus upon only one type of noise exposure, such as aircraft or road traffic noise. Studies that have examined ambient noise and, thus, exposure to more than one source (e.g. Lercher, Evans, Meis, & Kofler, 2002) have not been able to attribute health effects to specific noise sources within the environment. Little is known about the effects on health of combined exposure and it is possible that combined exposure has a cumulative impact or it could be synergistic (see Nilsson & Berglund, 2001). Furthermore, noise exposure often co-occurs with air pollution, because of source-specificity, and studies have yet to explore the implications of probable interactions between noise and air pollution for human health.

Annoyance

It is beyond the limits of this paper to include a review of the effect of noise exposure on annoyance responses. Annoyance is a multifaceted psychological concept including both evaluative and behavioral components (Guski, Schuemer, & Felscher-Shur, 1999), used to describe negative reactions to noise. Annoyance is an important health effect of noise (WHO, 2000). Annoyance is the most reported problem caused by transport noise exposure and is often the primary outcome used to evaluate the effect of noise on communities. Acoustic factors such as noise source, exposure level and time of day of exposure only partly determine an individual's annoyance response: many non-acoustical factors such as the extent of interference experienced, ability to cope, expectations, fear associated with the noise source, noise sensitivity, anger, and beliefs about whether noise could be reduced by those responsible influence annoyance responses (WHO, 2000). Studies have derived exposure-effect associations for the effects of different noise sources on annoyance responses (Miedema & Vos, 1998; Miedema & Oudshoorn, 2001), finding that aircraft noise produces greater annoyance responses than road traffic noise at the same level of exposure.

Hypertension & Coronary Heart Disease

Epidemiological evidence for effects of noise on coronary heart disease and coronary risk factors in adults has been mixed. These inconsistencies may be attributable to the use of varying outcome measures, ranging from weaker self-report measures of hypertension and drug use to more objective measures of blood pressure: as well as to whether confounding factors associated with coronary heart disease such as age, gender, smoking, and body mass index have been taken into account.

Evidence for effects of transport noise exposure on hypertension and ischaemic heart disease is strengthening (Babisch, 2006a). The unique multi-centre HYENA study found increased risk of hypertension related to long-term noise exposure, for both night-time aircraft noise and daily average road traffic noise, for individuals who had lived near to one of six major European airports for five years or more (Jarup et al., 2008). The analyses adjusted for important confounders (age, gender, body mass index, alcohol intake, physical activity, education) and had a good measure of hypertension based upon blood pressure measurements, supplemented by self-reports of a diagnosis of hypertension and/or use of anti-hypertensive medication. Another recent study demonstrated an effect of aircraft noise exposure on the use of anti-hypertensive drugs around Cologne-Bonn airport, particularly for those exposed to night noise (Greiser, Greiser, & Janhsen 2007): however, no data about confounding factors was included in the analyses. A study of road traffic noise and medication use which did adjust for confounders found an effect but only for subjects between 45-55 years and for those exposed to >55 dBA L_{den} (de Kluizenaar, Gansevoort, Miedema, & de Jong, 2007). A study of over 28,000 blood pressure records from around Kadena airport in Okinawa, Japan, found a dose-response relationship between aircraft noise exposure and systolic blood pressure (Odds ratio (OR)=1.29 95% Confidence Intervals (CI)=1.13-1.47) after taking age, gender and body mass index into account: however, no effect was found for diastolic blood pressure, although a weaker measure of self-reported hypertension did show an association with noise exposure (Matsui et al., 2001). Similarly, a study around Arlanda airport in Sweden found that self-reported hypertension was more prevalent among people exposed to average aircraft noise levels of at least 55dBA (LA_{eq}) or maximum levels above 72 dBA (L_{Amax}), after taking age, gender, smoking and education into account (Rosenlund, Berglind, Pershagen, Jarup, & Bluhm, 2001). A recent Swedish study found an association between road traffic noise exposure and self-reported hypertension, after taking age, gender, smoking, occupation and house type into account (Bluhm, Berglind, Nordling, & Rosenlund, 2007): (OR=1.38 95%CI 1.06-1.80 per 5dBA increase in noise exposure). Associations were stronger for those who had lived at the address for more than 10 years and for females. However, a German study of incidence of myocardial infarction found an effect of road traffic noise only for males who had lived at their address for at least 10 years (Babisch, Beule, Schust, Kersten, & Ising, 2005). An effect of aircraft noise on incidence of myocardial infarction has also been demonstrated for individuals exposed to >50 $L_{Aeq24\ hours}$, with stronger associations found for older subjects (Eriksson et al., 2007).

Meta-analyses have established that noise has a significant effect on risk for hypertension and coronary heart disease. A meta-analysis found that for aircraft noise a 5 dBA rise in noise was associated with a 25% increase in risk of hypertension compared with those not exposed to noise (van Kempen et al., 2002). Two meta-analyses of the effect of road traffic noise exposure on coronary heart disease, where outcomes ranged from blood pressure and hypertension to ischaemic heart disease and myocardial infarction found that environmental noise above 65-70dBA was associated with a 10 to 50% increase in risk (Babisch, 2000; 2006a). A recent study estimated that 3% of the total cases of myocardial infarction in Germany are attributable to road traffic noise (Babisch, 2006b).

There is some evidence for annoyance as a possible mediating factor between noise and cardiovascular outcomes. A ten year study of nearly 4000 men from Caerphilly in Wales, found that high annoyance at baseline predicted incidence of coronary heart disease many years later but only for men who were free of chronic disease at baseline: for men with chronic disease at baseline, noise exposure but not annoyance was associated with the incident of coronary heart disease (Babisch, Ising, & Gallacher 2003). This suggests that noise annoyance may have a moderating effect on the development of coronary heart disease. A recent study of 3000 residents in a city in Serbia found that men who were extremely annoyed by traffic noise had an increased risk of reporting hypertension and myocardial infarction, compared with those not annoyed; no similar relationship was observed for women (Belojevic & Saric-Tanaskovic, 2002). However, these cross-sectional findings should be treated cautiously, as men with cardiovascular disease may be more likely to develop annoyance in response to noise. Further, longitudinal research on annoyance as a mediating factor is required.

Epidemiological evidence for effects of noise on coronary risk factors in children has been mixed, which may be due to a number of methodological problems including lack of control for confounding factors, such as parental blood pressure, as well as being limited to considering the effect of noise exposure at school (van Kempen et al., 2006). A cross-sectional study around Schiphol (Amsterdam) and Heathrow (London) airports found an effect of aircraft noise at home, as well as night time aircraft noise exposure on systolic and diastolic blood pressure for 9-10 year old children but no effect for aircraft noise at school (van Kempen et al., 2007); these findings suggest that it may specifically be aircraft noise exposure during the evening and night that affects children's blood pressure. For road traffic noise exposure, this study found that exposure at school was associated with decreased systolic and diastolic blood pressure. A study of younger children, aged 3-7 years, found an association between night-time road traffic noise exposure at home and systolic blood pressure, as well as an effect of day-time road traffic noise exposure at kindergarten (Belojevic, Jakovljevic, Stojanov, Paunovic, & Ilic, 2007). Whilst these recent studies are methodologically stronger than previous studies, additional studies focusing on the effect of different noise sources, in different settings are required before further conclusions can be drawn about noise effects on children's blood pressure.

Stress Hormones

Studies of endocrine markers of noise exposure have demonstrated conflicting results. Adrenaline, noradrenaline and cortisol, all of which are released by the adrenal glands in situations of stress, have been examined. One difficulty in studying these hormones is that salivary and urinary measures of these hormones are easily biased by unmeasured factors; studies also often have small sample sizes. Cortisol, in particular, is difficult to examine, as it has diurnal variation and is usually high in the morning and low in the evening making it difficult to measure effectively.

Evidence of effects of road traffic noise exposure on endocrine markers in adults is weak and inconclusive (see Babisch, 2003): one study found an effect of being exposed to levels above 65 dBA for raised cortisol but not adrenaline levels, although this was on a sample of only 28 individuals (Poll, Straetemans, & Nicolson, 2001). A larger study found an effect of road traffic noise on noradrenaline but not adrenaline (Babisch, Froome, Beyer, & Ising, 2001).

The findings of studies of noise effects on endocrine markers in children are similarly mixed, despite larger sample sizes. Two of the largest studies to date, examining children living near Heathrow airport in West London, found no association between aircraft noise exposure above 66 dBA L_{Aeq} and morning salivary cortisol measures (Haines, Stansfeld, Job, Berglund, & Head, 2001a), nor, in a similar study, between aircraft noise exposure above 62 dBA L_{Aeq} and twelve-hour urinary cortisol, adrenaline and noradrenaline measures (Haines et al., 2001b).

Overall, further studies on the effects of noise on endocrine responses are required. Previous studies of adults are hampered by their small sample sizes, which may reflect the unwillingness of individuals to provide biological samples. As well as inconclusive evidence, little is known about whether raised endocrine responses observed in some studies represent normal short-term responses to environmental stress or a longer-term activation of the endocrine system. There is a lack of understanding about how long-term activation of the endocrine system links to health impairment and whether endocrine responses can habituate to noise exposure is not certain.

Sleep Disturbance

Exposure to night-time noise can potentially interfere with the ability to fall asleep, shorten sleep duration, cause awakenings and reduce perceived quality of sleep (Michaud, Fidell, Pearsons, Campbell, & Keith, 2007) and could affect health in two ways. Firstly, by impacting on biological responses, such as increasing heart rate, awakenings and sleep quality, as the individual responds to stimuli in the environment (HCN, 2004). Activation of some biological responses could have long-term effects on health. Secondly, sleep disturbance can impact on well-being, causing annoyance, irritation, low mood, fatigue, and impaired task performance (HCN, 2004). In terms of noise exposure, it has been suggested that continuous noise exposure is more likely to interrupt REM sleep, whilst intermittent noise is more likely to interfere with slow wave sleep (Passchier-Vermeer, Vos, Steenbekkers, van der Ploeg, & Groothuis-Oudshoorn, 2002).

Research on evidence for an effect of noise exposure on sleep disturbance is generally stronger from laboratory studies than from field studies. However, comparison between the findings of laboratory and field studies can be limited as laboratory studies tend to involve individuals who are not chronically exposed to noise, whereas, individuals who are chronically exposed to noise may exhibit habituation, where sleep disturbance becomes diminished, following a period of chronic noise exposure. A notable recent laboratory study tried to simulate the effect of aircraft noise exposure on sleep for 128 subjects over 13 nights (Basner & Samel, 2005). Prior to the experiment, the subjects spent a noise-free adaptation night in the laboratory, as sleep is initially affected by the laboratory setting. The experiment demonstrated a prominent first night exposure effect of noise on sleep disturbance, which wore off by the second night, which was interpreted as indicating habituation to noise exposure. On the subsequent nights no significant change in sleep structure was observed if the number of noise events and maximum sound pressure level did not exceed 4*80dB, 8*70dB, 16*60dB, 32*55dB, and 64*45dB. However, this study is still limited by having examined short-term exposure to aircraft noise, and conclusions cannot be drawn from these findings about the long-term effects of exposure to aircraft noise on sleep structure (Basner & Samel, 2005).

Overall, community studies of noise exposure, examining individuals in their homes exposed to their usual noise exposures at night, have found evidence for a direct effect of noise on sleep disturbance. However, recent reviews, assessing the strength of the evidence, differ in their conclusions. A recent synthesis of field studies concluded that there was sufficient evidence that night-time noise exposure was causing direct biological responses, at approximately 40dB SEL (Sound Exposure Level), as well as affecting well-being and quality of sleep (HCN, 2004). This report found that evidence was weaker for an effect of night-time noise on social interaction, task performance, on specific disease symptoms or on fatal accidents at work. Similarly, a meta-analysis of 24 field studies, including almost 23,000 individuals exposed to night-time noise levels ranging from 45-65dBA, found that aircraft noise was associated with greater self-reported sleep disturbance than road traffic, and road traffic noise with greater disturbance than railway noise (Miedema & Vos, 2007). This analysis also found an inverted U-shaped association between noise induced sleep disturbance and age, with the greatest disturbance being found for individuals aged 50-56 years. The study concluded that transportation noise was a widespread factor affecting sleep.

In contrast, a recent review focusing solely on aircraft noise exposure concluded that findings about noise-induced sleep disturbance differ considerably (Michaud et al., 2007). The review of five studies found little evidence for an effect of outdoor noise on sleep disturbance, whilst indoor noise was associated more closely with sleep outcomes. However, there was evidence from several studies that a greater number of awakenings occur that are either spontaneous or attributable to other noise in the home, than are attributable to aircraft noise.

The equivocal conclusions of these reviews may be because the studies are comparing studies which examine a range of outcomes ranging from more objective measures of sleep disturbance, such as polysomnography and wrist-actimetry, which measures sleep disturbance based on body movements, to subjective measures, such as self-reported sleep disturbance. The measurement of sleep disturbance is challenging, as no one physical or psychological measure is accurate or reliable. The equivocal conclusions may also reflect different exposure assessments: some studies use external noise exposure, whilst others measure noise exposure in the bedroom (Miedema & Vos, 2007).

Evidence from recent studies where change in night-time noise exposure has occurred also provides some evidence for an association between noise and sleep disturbance. Whilst a Swedish study found that a reduction in road traffic noise exposure caused by a new road tunnel was associated with improvements in sleep quality and alertness, measured by actimetry and subjective reports (Öhrström, 2002), a change in night-time aircraft noise exposure at two airports was not associated with changes in noise induced sleep disturbance (Fidell, Pearsons, Tabachnick, & Howe, 2000). Few studies have included children in studies of sleep disturbance: one study used sleep logs and actigraphy to compare the effect of road traffic noise on child and parent sleep, finding an exposure-effect relationship between road traffic noise exposure and sleep quality and daytime sleepiness for children, and an exposure effect association between road traffic noise and sleep quality, awakenings, and perceived interference from noise for the parents (Öhrström, Hadzibajramovic, Holmes, & Svensson, 2006).

In conclusion, overall, there is sufficient evidence that night-noise can disturb sleep, as well as potentially affect well-being. The field still lacks longitudinal evidence, which would enable the causal association between noise exposure and the long-term health implications of biological responses and impaired well-being, related with night-time noise exposure to be examined.

Psychological Health

Given the effect of chronic noise exposure on annoyance responses, it has been hypothesized that chronic noise exposure could have a serious effect on psychological health, as noise can cause annoyance and prolonged annoyance could lead to poor psychological health (McLean & Tarnopolsky, 1977). The effect of noise on psychological health is complicated as studies have found that poorer psychological health is also associated with greater annoyance responses (Tarnopolsky, Barker, Wiggins, & McLean 1978; van Kamp, Houthuijs, van Wiechen, & Breugelmans, 2007) and greater noise sensitivity (Stansfeld, Clark, Jenkins, & Tarnopolsky, 1985; Miyakawa, Matsui, & Hiramatsu, 2007).

Studies of adults have found that noise exposure relates to an increase in the number of psychological symptoms reported, such as symptoms of anxiety and depression, rather than to clinically diagnosable psychiatric disorders (Tarnpolsky et al., 1978; Stansfeld, Sharp, Gallacher, & Babisch, 1993). A later study examined nearly 6000 inhabitants around two military airbases in Japan, and found that those exposed to noise levels of 70 L_{dn} or above had higher rates of mental instability and depressiveness (Hiramatsu, Yamamoto, Taira, Ito, & Nakasone, 1997). Additionally, those who were more annoyed showed higher risk of mental and somatic symptoms. Unfortunately, this study did not assess psychiatric diagnoses, but a recent study has found associations between noise exposure and psychiatric diagnoses as measured by the Composite International Diagnostic Interview (Hardoy et al., 2005), with individuals living close to an airport showing higher frequency of 'generalized anxiety disorder' and 'anxiety disorder not otherwise specified', compared with matched controls from another area. These findings need replication and unfortunately, it is not possible to distinguish cause from effect in these studies, which are all cross-sectional, measuring noise and psychological health concurrently. A longitudinal study around Schiphol airport in Amsterdam found no association between noise exposure levels and mental health either at baseline, or after the opening of a fifth runway (van Kamp et al., 2007).

Several recent studies have examined associations between noise exposure and children's psychological health. The Tyrol Mountain Study compared child and teacher ratings of psychological health for children exposed either to <50 or > 60 dBA L_{dn} (Lercher et al., 2002). Ambient noise (road and rail) exposure was associated with teacher ratings of psychological health but was only associated with child rated psychological health for children with early biological risk (low birth weight or premature birth). A study of children attending school near Heathrow airport in London also found that noise exposed children had higher levels of psychological distress (Haines et al., 2001b), as well as a higher prevalence of hyperactivity. The RANCH study, the largest study of road traffic and aircraft noise exposure on children's psychological health to date, failed to replicate an effect of either aircraft or road traffic noise on psychological distress in samples from the Netherlands, Spain or the UK (Stansfeld et al., 2005): however, the effect of aircraft noise on hyperactivity was replicated.

Overall, studies suggest that for both adults and children noise exposure is probably not associated with serious psychological illness but there may be effects on well-being and quality of life: this conclusion is limited by the lack of longitudinal research in this field. There is a need for further research, especially to establish if hyperactive children are more susceptible to stimulating environmental stressors such as noise.

Cognitive Development

It has been suggested that children may be especially vulnerable to effects of environmental noise as they may have less cognitive capacity to understand and anticipate environmental stressors, as well as a lack of developed coping repertoires (see Stansfeld, Haines, & Brown, 2000). Exposure during critical periods of learning at school could potentially impair development and have a lifelong effect on educational attainment. Whilst a recent study suggests that children may not be more susceptible to environmental noise effects on cognitive performance than adults (Boman, Enmarker, & Hygge, 2005), studies have established that children exposed to noise at school experience some cognitive impairments, compared with children not exposed to noise: tasks affected are those involving central processing and language such as reading comprehension, memory and attention (Haines et al. 2001a; 2001b; Evans & Maxwell, 1997; Cohen, Glass, & Singer, 1973).

One of the most interesting and compelling studies in this field is the naturally occurring longitudinal quasi-experiment reported by Evans and colleagues, examining the effect of the relocation of Munich airport on children's health and cognition (Evans, Hygge, & Bullinger, 1995; Evans, Bullinger & Hygge, 1998; Hygge, Evans, & Bullinger, 2002). In 1992 the old Munich airport closed and was relocated. Prior to relocation, high noise exposure was associated with deficits in long term memory and reading comprehension. Two years after the closure of the airport, these deficits disappeared, indicating that noise effects on cognition may be reversible if exposure to the noise ceases. Most convincing was the finding that deficits in memory and reading comprehension developed over the two year follow-up for children who became newly noise exposed near the new airport.

The recent large scale RANCH study, which compared the effect of road traffic and aircraft noise on children's cognitive performance in the Netherlands, Spain and the UK, found a linear exposure-effect relationship between chronic aircraft noise exposure and impaired reading comprehension and recognition memory, after taking a range of socioeconomic and confounding factors into account (Stansfeld et al., 2005). No associations were observed between chronic road traffic noise exposure and cognition, with the exception of episodic memory, which surprisingly showed better performance in high road traffic noise areas. Neither aircraft noise nor road traffic noise affected attention or working memory. In terms of the magnitude of the effect of aircraft noise on reading comprehension, a 5dBA L_{eq16} increase in aircraft noise exposure was associated with a 2 month delay in reading age in the UK and a 1 month delay in the Netherlands (Clark et al., 2006): this association remained after adjustment for aircraft noise annoyance and cognitive abilities including episodic memory, working memory and attention. Thus, whilst aircraft noise has only a small effect on reading comprehension, it is possible that children may be exposed to aircraft noise for many of their childhood years and the consequences of long-term noise exposure on reading comprehension and further cognitive development remain unknown.

The findings of the RANCH study, along with previous findings (Haines et al., 2001b; Hygge et al., 2002) suggest that noise may directly affect reading comprehension or could be accounted for by other mechanisms including teacher and pupil frustration (Evans & Lepore, 1993), learned helplessness (Evans & Stecker, 2004) and impaired attention (Cohen et al., 1973; Evans & Lepore, 1993). It has been suggested that children may adapt to chronic noise exposure by filtering or tuning out the unwanted noise stimuli: this filter may then be applied indiscriminately to situations where noise is not present, leading to learning deficits through lack of attention.

Discussion

In summary, there is convincing evidence for non-auditory effects of noise on health and cognition for some outcomes. Evidence for the effect of aircraft noise on children's cognitive performance is strong. Evidence for health outcomes is increasing and there is consistent evidence for a small but significant effect of transport noise on hypertension and coronary heart disease. Furthermore, there is sufficient evidence for an effect of noise on sleep disturbance. Evidence for an effect of noise on endocrine markers is weak and inconclusive, especially for adults. Health effects of noise on the endocrine system cannot yet be ruled out and further, large scale studies are required focusing on adults.

Evidence for an effect of noise on psychological health suggests that for both adults and children noise is probably not associated with serious psychological ill-health but may affect quality of life and well-being. As yet, there are no prospective studies published on the effects of noise exposure on psychological health and few studies examine psychiatric diagnoses. The conclusions from cross-sectional evidence should be treated cautiously, as individuals who are experiencing poor mental health are more likely to also evaluate the environment negatively, bringing into question the direction of causality between noise exposure and mental health.

In conclusion, noise is a main cause of environmental annoyance and it negatively affects the quality of life of a large proportion of the population. In addition, health and cognitive effects, although modest, may be of importance given the number of people increasingly exposed to environmental noise and the chronic nature of exposure. Future research needs to further develop understanding not only of the magnitude of effects and exposure-effect relationships, which can inform interventions and policy, but also needs to further consider mechanisms for the effects such as the role of annoyance, adaptation, habituation, acclimation, and coping strategies and the role these may play in non-auditory effects of noise.

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