

Noise pollution: non-auditory effects on health

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Noise is a prominent feature of the environment including noise from transport, industry and neighbours. Exposure to transport noise disturbs sleep in the laboratory, but not generally in field studies where adaptation occurs. Noise interferes in complex task performance, modifies social behaviour and causes annoyance. Studies of occupational and environmental noise exposure suggest an association with hypertension, whereas community studies show only weak relationships between noise and cardiovascular disease. Aircraft and road traffic noise exposure are associated with psychological symptoms but not with clinically defined psychiatric disorder. In both industrial studies and community studies, noise exposure is related to raised catecholamine secretion. In children, chronic aircraft noise exposure impairs reading comprehension and long-term memory and may be associated with raised blood pressure. Further research is needed examining coping strategies and the possible health consequences of adaptation to noise.

Introduction

Noise, defined as ‘unwanted sound’, is perceived as an environmental stressor and nuisance. Non-auditory effects of noise, as dealt with in this chapter, can be defined as ‘all those effects on health and well-being which are caused by exposure to noise, with the exclusion of effects on the hearing organ and the effects which are due to the masking of auditory information (*i.e.* communication problems)¹.

Exposure to continuous noise of 85–90 dBA, particularly over a lifetime in industrial settings, can lead to a progressive loss of hearing, with an increase in the threshold of hearing sensitivity². Hearing impairments due to noise are a direct consequence of the effects of sound energy on the inner ear. However, the levels of environmental noise, as opposed to industrial noise, are much lower and effects on non-auditory health cannot be explained as a consequence of sound energy.

If noise does cause ill-health other than hearing impairment, what might be the mechanism? It is generally believed that noise disturbs activities and communication, causing annoyance. In some cases, annoyance may

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lead to stress responses, then symptoms and possibly illness³. Alternatively, noise may influence health directly and not through annoyance. The response to noise may depend on characteristics of the sound, including intensity, frequency, complexity of sound, duration and the meaning of the noise.

Non-auditory effects of noise on health

Noise and sleep disturbance

There is both objective and subjective evidence for sleep disturbance by noise⁴. Exposure to noise disturbs sleep proportional to the amount of noise experienced in terms of an increased rate of changes in sleep stages and in number of awakenings. Habituation occurs with an increased number of sound exposures by night and across nights. One laboratory study, however, found no habituation during 14 nights of exposure to noise at maximum noise level exposure⁵. Objective sleep disturbance is likely to occur if there are more than 50 noise events per night with a maximum level of 50 dBA indoors or more. In fact, there is a low association between outdoor noise levels and sleep disturbance.

In the Civil Aviation Authority Study⁶ around Heathrow and Gatwick airports, the relative proportion of total sleep disturbance attributable to noise increased in noisy areas but not the level of total sleep disturbance. In effect, the work suggested a symptom reporting or attribution effect rather than real noise effects. In a subsequent actigraphy study around four UK airports, sleep disturbance was studied in relation to a wide range of aircraft noise exposure over 15 consecutive nights⁷. Although there was a strong association between sleep EEGs and actigram-measured awakenings and self-reported sleep disturbance, none of the aircraft noise events were associated with awakenings detected by actigram and the chance of sleep disturbance with aircraft noise exposure of <82 dB was insignificant. Although it is likely that the population studied was one already adapted to aircraft noise exposure, this study is also likely to be closer to real life than laboratory studies with subjects newly exposed to noise. However, the actigraph as a sensitive measure of sleep disturbance has been questioned.

Noise exposure during sleep may increase blood pressure, heart rate and finger pulse amplitude as well as body movements. There may also be after-effects during the day following disturbed sleep; perceived sleep quality, mood and performance in terms of reaction time all decreased following sleep disturbed by road traffic noise. Studies on noise abatement show that, by reducing indoor noise level, the amount of REM sleep and slow wave sleep can be increased⁸. It thus seems that, although there may

be some adaptation to sleep disturbance by noise, complete habituation does not occur, particularly for heart rate.

Noise exposure and performance

There is good evidence, largely from laboratory studies, that noise exposure impairs performance⁹. Performance may be impaired if speech is played while a subject reads and remembers verbal material, although this effect is not found with non-speech noise¹⁰. The effects of 'irrelevant speech' are independent of the intensity and meaning of the speech. The susceptibility of complex mental tasks to disruption by 'irrelevant speech' suggests that reading, with its reliance on memory, may also be impaired.

Perceived control over and predictability of noise has been found to be important in determining effects and after-effects of noise exposure. Glass and Singer¹¹ found that tasks performed during noise were unimpaired but tasks that were carried out after noise had been switched off were impaired, this being reduced when subjects were given perceived control over the noise. Indeed, even anticipation of a loud noise exposure in the absence of real exposure may impair performance and an expectation of control counters this effect. Noise exposure may also slow rehearsal in memory, influence processes of selectivity in memory, and choice of strategies for carrying out tasks¹. There is also evidence that noise may reduce helping behaviour, increase aggression and reduce the processing of social cues seen as irrelevant to task performance¹².

Noise and cardiovascular disease

Physiological responses to noise exposure

Noise exposure causes a number of predictable short-term physiological responses mediated through the autonomic nervous system. Exposure to noise causes physiological activation including increase in heart rate and blood pressure, peripheral vasoconstriction and thus increased peripheral vascular resistance. There is rapid habituation to brief noise exposure but habituation to prolonged noise is less certain⁸.

Occupational studies: noise and high blood pressure

The strongest evidence for the effect of noise on the cardiovascular system comes from studies of blood pressure in occupational settings¹³ (Table 1). Many occupational studies have suggested that individuals chronically exposed to continuous noise at levels of at least 85 dB have higher blood pressure than those not exposed to noise^{14,15}. In many of these studies, noise exposure has also been an indicator of exposure to other factors, both physical and psychosocial, which are also associated with high blood

Table 1 Occupational studies of noise exposure and blood pressure

Reference	Type of study	Sample	Sample size	Noise intensity	Health measures	Hypertension risk factors controlled for	Findings
Herbold <i>et al</i> , 1989 ⁸²	Cross-sectional	Community sample of men 30–69 years	1046	Self report road traffic noise	SBP >160 mm	Age, BMI, Alcohol consumption	Stratified results indicate noise relates to hypertension. Not confirmed in multivariate analysis SBP, DBP raised in younger but not older worker
Green <i>et al</i> , 1991 ⁸³	Cross-sectional	Israeli male industrial workers	191	74–102 dBA	Hg DBP >95 mmHg	Age, involvement in physical work, smoking, Quieteleths Index, hearing loss, using of hearing protectors	SBP, DBP raised in younger but not older worker
Zhao <i>et al</i> ¹⁴	Cross-sectional	Female Chinese textile mill employees	1101	75–104 dBA	SBP >160 mmHg	Age, years of work, salt intake, family history of hypertension	Dose–response relationships in SBP and DBP
Lang <i>et al</i> ¹⁵	Cross-sectional	Parisian workers	7679	>85 dBA/8 h day	DBP >95 mmHg	Age, BMI, alcohol consumption, occupational category	SBP, DBP related to noise. Not confirmed in multivariate analysis
Fogari <i>et al</i> , 1994 ⁸⁴	Case control	Workers in a metallurgical factory	8811	>80 dB (n = 8078) versus >80dB (n = 733)	DBP > 95 mmHg	Age, BMI, duration of employment	Heart rate, DBP not differ SBP higher in noise
Hessel and Sluis-Cremer, 1994 ⁸⁵	Cross-sectional prospective	White South African miners	2197	80 dBA	SBP > 140 mmHg; DBP > 90 mmHg	Age, BMI	No noise effects on blood pressure
Kristal-Boneh <i>et al</i> , 1995 ⁸⁶	Cross-sectional	Blue collar workers from 21 Israeli industrial plants 60% response rate	3105	Means only used	Means only used	Age, smoking, coffee and cholesterol, industrial sector, physical work load	Noise exposure correlates with resting heart rate (significant in men) and DBP only in women. Intensity of noise exposure significantly associated to resting HR in women

pressure. Unless these other risk factors are controlled, spurious associations between noise and blood pressure may arise. A recent pioneering longitudinal industrial noise study has shown that noise levels predicted raised systolic and diastolic pressure in those doing complex but not simple jobs¹⁶, and predicts increased mortality risk. Occupational noise exposure has also recently been linked to greater risk of death from motor vehicle injury¹⁷. One possibility is that the effects of noise on blood pressure are mediated through an intermediate psychological response such as noise annoyance¹⁸ although this has not been convincingly proved.

Noise and cardiovascular disease in the community

Aircraft noise exposure around Schiphol Airport, Amsterdam has been related to more medical treatment for heart trouble and hypertension, more cardiovascular drug use and higher blood pressure, even after adjustment for age, sex, smoking, height/weight and socio-economic differences¹⁹. The evidence of the effects of noise on coronary risk factors has not been especially consistent: effects of noise have been shown on systolic blood pressure (but not diastolic pressure), total cholesterol, total triglycerides²⁰, blood viscosity, platelet count and glucose level²¹. However, a recent Swedish study found that the prevalence of hypertension was higher among people exposed to time-weighted energy averaged aircraft noise levels of at least 55 dBA or maximum levels above 72 dBA around Arlanda airport, Stockholm²². In summary, there is some evidence from community studies that environmental noise is related to hypertension and there is also evidence that environmental noise may be a minor risk factor for coronary heart disease (Relative Risk 1.1–1.5)^{22–24}.

A sudden intense exposure to noise may stimulate catecholamine secretion and precipitate cardiac dysrhythmias. However, neither studies in coronary care units of the effect of speech noise nor studies of noise from low altitude military flights on patients on continuous cardiac monitoring have detected changes in cardiac rhythm attributable to noise²⁵.

Endocrine responses to noise

Exposure to high intensity noise in industry has been linked in some studies to raised levels of noradrenaline and adrenaline²⁶. In one study, catecholamine secretion decreased when workers wore hearing protection against noise. Some studies, but not all, have shown raised cortisol in relation to noise²⁷. The general pattern of endocrine responses to noise is indicative of noise as a stressor, exciting short-term physiological responses, but there are inconsistencies between studies.

Noise and psychiatric disorder

It has been postulated that noise exposure creates annoyance which then leads on to more serious psychological effects. This pathway remains unconfirmed; rather it seems that noise causes annoyance and, independently, mental ill-health also increases annoyance. A more complex model²⁸ incorporates the interaction between the person and their environment. In this model, the person readjusts their behaviour in noisy conditions to reduce exposure. An important addition is the inclusion of the appraisal of noise (in terms of danger, loss of environmental quality, meaning of the noise, challenges for environmental control, *etc.*) and coping (the ability to alter behaviour to deal with the stressor). This model emphasizes that dealing with noise is not a passive process.

Noise exposure and psychological symptoms

Symptoms reported among industrial workers regularly exposed to high noise levels in settings such as schools²⁹ and factories³⁰ include nausea, headaches, argumentativeness and changes in mood and anxiety. Many of these industrial studies are difficult to interpret, however, because workers were exposed to other stressors such as physical danger and heavy work demands, in addition to excessive noise. Community surveys have found that high percentages of people reported 'headaches', 'restless nights', and 'being tense and edgy' in high-noise areas^{12,31}. An explicit link between aircraft noise and symptoms emerging in such studies raised the possibility of a bias towards over-reporting of symptoms³². Notably, a study around three Swiss airports³³, which did not mention that it was related to aircraft noise, did not find any association between the level of exposure to aircraft noise and symptoms.

Noise and common mental disorder

Early studies found associations between the level of aircraft noise and psychiatric hospital admission rates both in London³⁴ and Los Angeles³⁵, but this has not been convincingly confirmed by more recent studies³⁶. In community studies such as the West London Survey of Psychiatric Morbidity³⁷, no overall relationship was found between aircraft noise and the prevalence of psychiatric morbidity using various indices of noise exposure. In longitudinal analyses in the Caerphilly Study, no association was found between road traffic noise and psychiatric disorder, even after adjustment for socio-demographic factors and baseline psychiatric disorder, although there was a small non-linear association of noise with increased anxiety scores³⁸.

Some studies have found dose-response associations: exposure to higher levels of military aircraft noise around Kadena airport in Japan was related in a dose-response relationship to depressiveness and nervousness³⁹,

and road traffic noise has been weakly associated with mental health symptoms after adjusting for age, sex, income and length of residence⁴⁰. Overall, environmental noise seems to be linked to psychological symptoms but not to clinical psychiatric disorder. However, there may be a link to psychiatric disorder at much higher noise levels.

Noise annoyance

The most widespread and well documented subjective response to noise is annoyance, which may include fear and mild anger, related to a belief that one is being avoidably harmed⁴¹. Noise is also seen as intrusive into personal privacy, while its meaning for any individual is important in determining whether that person will be annoyed by it⁴².

Annoyance reactions are often associated with the degree of interference that any noise causes in everyday activities, which probably precedes and leads on to annoyance⁴³. In both traffic and aircraft noise studies, noise levels have been found to be associated with annoyance in a dose-response relationship^{44,45}. Overall, it seems that conversation, watching television or listening to the radio (all involving speech communication) are the activities most disturbed by aircraft noise while traffic noise, if present at night, is most disturbing for sleep.

Acoustic predictors of noise annoyance in community surveys

One of the primary characteristics affecting the unwantedness of noise is its loudness or perceived intensity. Loudness comprises the intensity of sound, the tonal distribution of sound and its duration. The evidence is mixed on the importance of both the duration and the frequency components of sound and also the number of events involved in determining annoyance⁴⁶. High frequency noise has been found to be more annoying than low frequency noise⁴⁷. Vibrations are perceived as a complement to loud noise in most community surveys of noise and are found to be important factors in determining annoyance, particularly because they are commonly experienced through other senses as well as hearing. Fields⁴⁸ found that, after controlling for noise level, noise annoyance increases with fear of danger from the noise source, sensitivity to noise, the belief that the authorities can control the noise, awareness of the non-noise impacts of the source and the belief that the noise source is not important.

Combined effects of noise exposure and other stressors

Noise effects on health may be augmented by, or in turn may augment, the impact of other stressors on health. Stressors may act synergistically, antagonistically or not at all. Stressors may include physical, chemical,

biological, social and work organizational factors⁴⁹. In a laboratory based experiment, an interaction was found between having a cold and noise exposure on simple reaction time⁵⁰. There was little difference between healthy and cold subjects' performance tested in quiet conditions, but for subjects tested in noisy conditions (70 dBA), performance was much slower for the cold subjects. Synergistic effects of exposure to noise and vibration have been demonstrated on diastolic blood pressure, whereas temperature and noise have been shown to affect morning adrenaline secretion^{51,52}.

There has been much emphasis on laboratory studies without considering that results of such studies may lack external validity. Past research on combined effects has not considered common conditions and levels of stressors across studies, direct and indirect effects, long durations of exposure and complex tasks. Field studies suggest that the effects of multiple stressors have greater combined effects than simply summing individual stressors⁵³. Few field studies have examined the effects of multiple environmental stressors. This could be an important new area for the development of noise research.

Noise and non-auditory health effects in children

It is likely that children represent a group which is particularly vulnerable to the non-auditory health effects of noise. They have less cognitive capacity to understand and anticipate stressors and lack well-developed coping strategies^{54,55}. Moreover, in view of the fact that children are still developing both physically and cognitively, there is a possible risk that exposure to an environmental stressor such as noise may have irreversible negative consequences for this group.

Cognition

Studies of children exposed to environmental noise have consistently found effects on cognitive performance. The studies which are most informative in terms of the effects of noise on cognition have been field studies focusing on primary school children. This article will focus on these studies. For details of noise effects on pre-school children and of laboratory studies of acute noise exposure, see Ref. 56.

The effects of noise have not been found uniformly across all cognitive functions. The research evidence suggests that chronic exposure to noise affects cognitive functions involving central processing and language comprehension. The effects which have been found can be summarized as follows. Deficits have been found in sustained attention and visual attention⁵⁷⁻⁶². Relatedly, according to teachers' reports, noise-exposed children have difficulties in concentrating in comparison with children

from quieter schools^{2,63}. Children exposed to chronic environmental noise have been found to have poorer auditory discrimination and speech perception^{54,60,64–67} as well as poorer memory requiring high processing demands^{56,68,69}. Finally, chronically exposed children tend to have poorer reading ability and school performance on national standardized tests^{64,65,67,70–76}.

The first well-designed naturalistic field study to examine the effects of chronic noise exposure focused on primary school children living in four 32-floor apartment buildings adjacent to a major road⁶⁵. The rationale behind this study was that children in the lower floor of the apartment building would be exposed to higher amounts of noise from the road than those higher up the building. Seventy-three children were tested for auditory discrimination and reading level and the results indicated that children living on the lower floors had greater impairments on these measures than those living higher up the buildings.

A very well controlled study by Bronzaft and McCarthy⁷¹ compared primary school children taught in a classroom which was exposed to high levels of railway noise with children in a quiet classroom in the same school. Significant differences in reading scores were found between children in the two classrooms. In fact, the mean reading age of the noise-exposed children was 3–4 months behind that of the control children.

A series of studies have been carried out in schools around Heathrow Airport in west London. These studies have used repeated-measures designs to compare noise-exposed and control children. In the first of these studies⁷³, the cognitive performance and stress responses of 9- to 10-year-old children in four high noise schools were compared with those of children in four matched control schools. The results showed that, at baseline, the noise-exposed children had impaired reading comprehension and sustained attention after adjustment for age, main language spoken at home and social deprivation. The results at follow up 1 year later suggest that the children's further development in reading comprehension may be affected.

The second study to be conducted near Heathrow Airport⁷⁴ was a multi-level modelling study of national standardized test scores (SATs). The data for 11,000 eleven-year-old children were analysed in relation to aircraft noise exposure contours. The results showed that noise exposure was associated with performance on reading and maths tests in a dose-response function but that this was influenced by socio-economic factors. The most recent study to be carried out at Heathrow⁷⁵ compared the cognitive performance and stress responses of children in 10 high-noise schools with those of children in 10 matched control schools. The results indicated that children in the noise-exposed schools experienced greater annoyance and had poorer reading performance on the difficult items of a national standardized reading test.

Perhaps the most important of all the naturalistic field studies to examine the effects of noise exposure on children was that carried out in Munich in the 1990s. This prospective, longitudinal study was able to take advantage of a naturally occurring experiment in which the existing Munich Airport was closed down and a new airport was opened at another location. Data were collected at both sites across three testing waves, one before the closure of the old airport and opening of the new one and two afterwards. The mean age of children was 10.8 years. The cross-sectional results⁶⁴ showed that, at Wave 1, children at the old airport displayed effects on long-term episodic memory and reading comprehension. The longitudinal results⁷⁷ showed that after three waves of testing, children at the old airport had improvements in long-term memory, suggesting that this effect of noise exposure is reversible. Interestingly, by the third wave of testing children at the new airport were exhibiting deficits in long-term memory and reading comprehension, providing strong evidence for a causal link between noise exposure and cognitive effects.

Motivation

A number of studies have identified an association between chronic exposure to aircraft noise and decreased motivation^{54,64,66,78}. The results are however not consistent. In the Los Angeles Airport Study^{66,78} children exposed to chronic aircraft noise were less likely to solve a difficult puzzle involving a success or failure experience and were more likely to give up. In a follow-up 1 year later⁷⁸ the finding that noise-exposed children were less likely to solve a difficult puzzle was replicated, but the finding that the same children are more likely to give up on a difficult puzzle was not. In the Munich study⁶⁴, noise-exposed children gave up on an insoluble puzzle more quickly than their non noise-exposed counterparts.

Cardiovascular effects

In addition to effects on cognitive performance, there is evidence that chronic noise exposure may give rise to physiological effects in terms of raised blood pressure. In the Los Angeles Airport Study⁶⁶, chronic exposure to aircraft noise was found to be associated with raised systolic and diastolic blood pressure. These increases, although significant, were within the normal range and were not indicative of hypertension. At follow-up 1 year later⁷⁸, the findings were the same, showing that these effects had not habituated. In the Munich study, chronic noise exposure was found to be associated with both baseline systolic blood pressure and lower reactivity of systolic blood pressure to a cognitive task presented under acute noise. After the new airport opened, a significant increase in systolic blood pressure was observed providing evidence for a causal link between chronic noise exposure and raised blood pressure. No association was found between noise and diastolic blood pressure or reactivity.

Endocrine disturbance

The Munich Airport Study^{64,79} examined overnight, resting levels of urinary catecholamines (adrenaline and noradrenaline). In the cross-sectional study at the old airport, endocrine levels were significantly higher in the noise-exposed children, indicating raised stress levels. The longitudinal data reveal a sharp increase in catecholamine levels in noise-exposed children following the opening of the new airport. Cortisol levels were also examined but no significant differences were observed in either the cross-sectional or longitudinal data. This latter finding is consistent with that of one of the Heathrow Studies⁷⁵.

Noise annoyance

Studies have consistently found evidence that exposure to chronic environmental noise causes annoyance in children, even in young children^{64,57,71}. In Munich, noise-exposed children were found to be more annoyed by noise as indexed by a calibrated community measure. In London, child-adapted, standard self-report questions^{48,80} were used to assess annoyance and showed higher annoyance levels in noise-exposed children. In a follow-up 1 year later, the same result was found, suggesting that annoyance effects are not subject to habituation.

Conclusions

The evidence for effects of environmental noise on health is strongest for annoyance, sleep and cognitive performance in adults and children. Occupational noise exposure also shows some association with raised blood pressure. Dose-response relationships can be demonstrated for annoyance and, less consistently, for blood pressure. The effects of noise are strongest for those outcomes that, like annoyance, can be classified under 'quality of life' rather than illness. What these effects lack in severity is made up for in numbers of people affected, as these responses are very widespread.

It may be that the risk of developing mental or physical illness attributable to environmental noise is quite small, although it is too soon to be certain of this in terms of the progress of research. Part of the problem is that the interaction between people, noise and ill-health is a complex one. Humans are not usually passive recipients of noise exposure and can develop coping strategies to reduce the impact of noise exposure. If people do not like noise they may take action to avoid it by moving away from noisy environments or, if they are unable to move away, by developing coping strategies. Active coping with noise may be sufficient to mitigate any ill-effects. Perception of control over the noise source may reduce the threat of noise and the belief that it can be harmful. It may also be

that noise is more harmful to health in situations where several stressors interact and the overall burden may lead to chronic sympathetic arousal or states of helplessness.

Adaptation to long-term noise exposure needs further study. Most people exposed to chronic noise, for instance from major airports, seem to tolerate it. Yet, questionnaire studies suggest that high levels of annoyance do not decline over time. Another possibility is that adaptation to noise is only achieved with a cost to health. Evans and Johnson⁸¹ found that maintaining task performance in noisy offices was associated with additional physiological effort and hormonal response.

Undoubtedly, there is a need for further research to clarify this complex area, including better measurement of noise exposure and health outcomes. Moreover, there should be a greater emphasis on field studies using longitudinal designs with careful choice of samples to avoid undue bias related to prior noise exposure.

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