CHAPTER

3

Environmental Noise and Health

3.1 INTRODUCTION

In urban areas, unwanted sounds (environmental noise) come overwhelmingly from road-based transportation but rail-based, airport transportation and industrial noise are also important sources. In the European Union (EU), problems with noise pollution have often been given similar concern ratings as those for global warming (CALM, 2007). In fact, results from the environmental burden of disease in Europe project show that traffic noise was ranked second among the selected environmental stressors evaluated in terms of their public health impact in six European countries (WHO, 2011), indicating the heightened awareness among the general public about noise pollution as an environmental issue. Moreover, a recent Eurobarometer survey showed that 44% of Europeans believe that noise affects human health to a 'large extent', an increase of 3% since 2006 (European Commission, 2010). The range of results for individual nations is shown in Figure 3.1 and indicates that the largest percentage of the population believing noise affects human health to a 'large extent' is in Italy (74%), while the lowest percentage is in Ireland (16%). In fact, Ireland is something of an oddity with 39% of the population of the opinion that noise has no impact on human health.

Very often, discourse concerning noise pollution implies and perhaps indeed overemphasises the negative aspects of the sound environment (Papadimitriou et al., 2009). But we are all aware, and indeed have direct experience, of sounds not only associated with negative feelings and emotions but also associated with positive ones, e.g., birds, music, etc. In this context, recent research around the sonic dimension of the landscape more generally has started to receive more attention in the academic literature (Mazaris et al., 2009). Here, this research is often referred to within the context of the concept of 'soundscape', a term coined by Schafer (1994) to describe perceptions of the acoustic environment in a landscape setting. Thus, while there are other more positive aspects of the sound

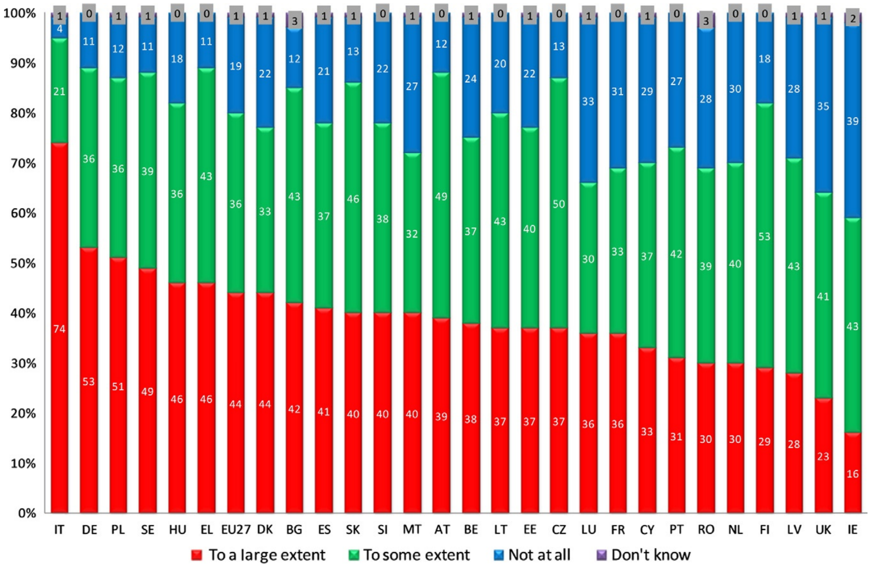

FIGURE 3.1 EU attitudes to the question of whether noise affects human health. *Source: EC (2010).*

environment being researched, it is clear that it is the negative aspects that have the greatest need for attention given their ability to impact public health and quality of life issues negatively. In this regard, the recent publication by the WHO (2011) of its seminal *Burden of Disease from Environmental Noise* document not only sets out the evidence base on the health effects of environmental noise in Europe but also attempts to quantify the extent of the problem. The document elucidates the extent to which noise pollution is a serious public health problem and that, contrary to the trend for other environmental stressors (e.g. second hand smoke, dioxins and benzene), which are declining, noise exposure is actually increasing in Europe and worldwide. Moreover, as further evidence of the growing recognition of noise as a health problem, the evidence emerging from the WHO document informed the recently established WHO European health policy – Health 2020.

3.2 THE NOISE–HEALTH PROBLEM

Table 3.1 shows a summary of the results from the WHO (2011) *Burden of Disease from Environmental Noise* study. The results are the first comprehensive effort at identifying the impact of excessive environmental noise on public health. The study concludes that one in three individuals in

TABLE 3.1 Burden of Disease from Environmental Noise in Europe

Noise-Induced Exposure	Public Health Impact
Annoyance	587,000 DALYs[a] lost for inhabitants in towns >50,000 population
Sleep disturbance	90,3000 DALYs for EUR-A[b] inhabitants in towns >50,000 population
Cardiovascular diseases	61,000 years for ischaemic heart disease in high-income European countries
Tinnitus[c]	22,000 DALYs for the EUR-A adult population
Cognitive impairment in children	45,000 DALYs for EUR-A countries for children aged 7–19 years

[a]*DALYs are the sum of the potential years of life lost due to premature death and the equivalent years of 'healthy' life lost by virtue of being in states of poor health or disability (WHO, 2011).*
[b]*EUR-A is a WHO epidemiological subregion in Europe comprising Andora, Austria, Belgium, Croatia, Cyprus, the Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Luxembourg, Malta, Monaco, the Netherlands, Norway, Portugal, San Marino, Slovenia, Spain, Sweden, Switzerland and the United Kingdom.*
[c]*Tinnitus is defined as the sensation of sound in the absence of an external sound source (WHO, 2011).*
Source: Adapted from WHO (2011).

Europe is annoyed during the daytime and one in five has disturbed sleep at night purely from traffic noise alone. The methodology devised in the WHO document to assess the burden of disease due to environmental noise represents the state of the art in risk assessment and quantification of the health effects of noise exposure. Much of the calculations are based on data taken from environmental noise maps constructed as part of EU member state requirements under the terms of the EU Environmental Noise Directive (END) detailed in the next chapter. This quantification of the scale of the public health problem associated with excessive environmental noise exposure is badly needed so that decision makers can gauge the nature and extent of the problem and determine the allocation of resources for mitigation.

The WHO (2011) methodology consists of calculating the burden of disease on the basis of the exposure–response relationship, exposure distribution, population-attributable fraction, background prevalence of disease and disability weights (DWs) of the outcome. The exposure–response relationship was derived from existing epidemiological studies or meta-analysis of published results. The incidence or prevalence of the health outcome in a population (e.g. for cardiovascular diseases) can be obtained by the national health statistics or surveys of the population. The *attributable fraction* is the proportion of disease in the population that is estimated to be caused by environmental noise. DW factors were used to reflect the severity of the disease on a scale from 0 (representing perfect health) to 1 (representing most imperfect health, i.e., death). The burden of disease is expressed in

FIGURE 3.2 Graphic description of the DALY. *Source: CC-by-sa Planemad/Wikipedia.*

terms of disability-adjusted life years (DALYs), which is the sum of potential years of life lost due to ill-health, disability or early death and the equivalent years of healthy life lost by virtue of being in states of poor health or disability. It is represented by the following equation:

$$\text{DALYs} = \text{YLD} + \text{YLL} \tag{3.1}$$

where YLD is years lived with disability and YLL is years of life lost.

One DALY is equivalent to 1 year of healthy life lost and is described graphically in Figure 3.2. Using this methodology, the report estimates that anywhere between 1 and 1.6 million healthy life years are lost every year from traffic-related noise in western European countries and this does not include estimates of the impact of daytime noise on shift workers.

BOX 3.1

THE DISABILITY-ADJUSTED LIFE YEAR

The DALY was originally developed by Harvard University for the World Bank and first used as input to the *World Bank's World Development Report 1993*: *Investing in Health*. Since then, it has been adopted by the World Health Organisation as a core metric for measuring the burden of disease in populations throughout the world. However, the metric has not been without its critics with Anand and Hanson (1997) describing it as '. . .flawed, and its assumptions and value judgements are open to serious question'.

We can see then that the impacts of noise pollution are highly significant and demonstrate the detrimental impacts of excessive environmental noise exposure on public health and overall quality of life. It is important to note that the burden of disease referred to in Table 3.1 relates to the non-auditory effects of environmental noise exposure. This is due to the fact that it has been well established for many decades that prolonged exposure to noise levels of relatively high degrees can lead to direct hearing loss and/or hearing impairment and the vast majority of this is related to occupational noise exposure (see Prasher, 2003). There is general agreement that exposure to sound levels less than 70 dB does not produce hearing damage, regardless of the duration of exposure (Goines and Hagler, 2007). At the same time, there is also agreement that exposure for more than 8 h to sound levels in excess of 85 dB(A) is potentially hazardous. However, environmental noise is not associated with any significant auditory effects because it is generally not associated with noise levels above 70 dB(A) for significant periods of time. As a result, noise pollution research over the last three decades has focussed on the relationship between noise exposure and related non-auditory health effects.

3.3 THE NOISE–STRESS RELATIONSHIP AND EFFECTS OVERVIEW

The noise–stress relationship is fairly well understood in principle. Noise activates the sympathetic and endocrine system. Specifically, it activates the pituitary–adrenal–cortical axis and the sympathetic–adrenal–medullary axis (Babisch, 2002). Changes in stress hormones are frequently found in acute and chronic noise experiments. Indeed, the results from laboratory studies have found changes in blood flow, blood pressure (BP) and heart rate in reaction to noise stimuli; they have also found increases in the release of stress hormones including catecholamines[1] adrenaline and noradrenaline, and the corticosteroid cortisol (Babisch, 2003).

In the medical literature, two principal pathways are relevant for the development of negative and adverse health effects resulting from noise exposure (Babisch, 2002): ‘direct’ and ‘indirect’ arousal and activation of the human organism (Figure 3.3). ‘Direct’ arousal is determined by the instantaneous interaction of the acoustic nerve with the various structures of the central nervous system. The ‘indirect’ pathway refers to the cognitive perception of sound (as noise), its cortical activation and related emotional responses whereby not only the noise level itself but subjective effects of noise annoyance has an association with negative health effects (Babisch et al., 2013). The ‘indirect’ pathway starts with noise-induced disturbances of activities such as communication and sleep. More pragmatically, noise tends to induce stress by disturbing sleep and interfering with relaxation and concentration as well as other cognitive effects that activate the sympathetic nervous system and the endocrine system (Babisch et al., 2001). As a result, both ‘direct’ and ‘indirect’ pathways can initiate physiological stress reactions which may result in a number of negative health effects especially as a result of long-term exposure.

[1]Catecholamines are hormones produced by the adrenal glands, which are found on top of the kidneys. They are released into the blood during times of physical or emotional stress.

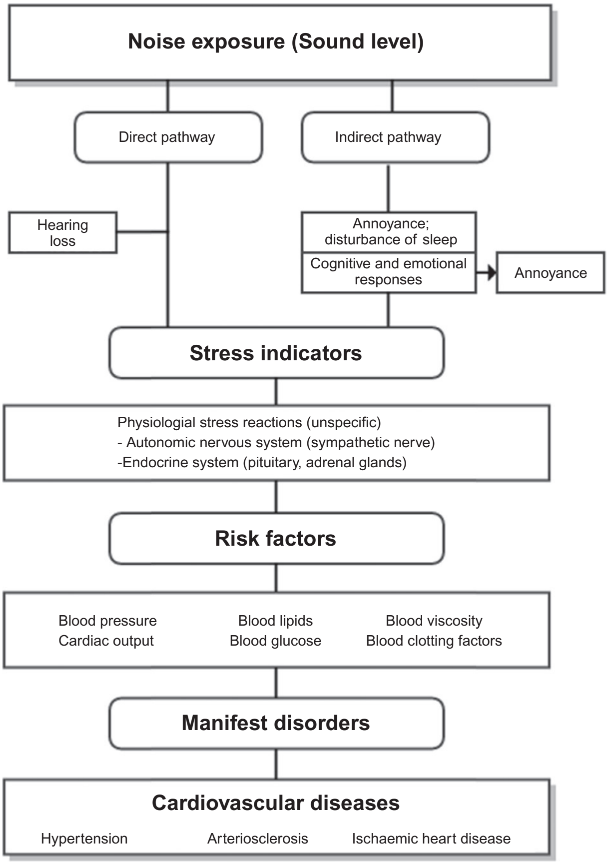

FIGURE 3.3 Noise effects reaction scheme. *Source: After Babisch (2002).*

Physiological experiments on humans have shown that noise exposure even at a moderate level acts via an indirect pathway and has health outcomes similar to those caused by high noise exposures on the direct pathway (WHO, 2009). Thus, acute noise effects occur not only at high sound levels but also at relatively low environmental sound levels when, rather importantly, physical recuperation might be taking place and when activities such as concentration, relaxation and sleep are disturbed (WHO, 2009). It is because of this relationship that the EU END recommends evaluating environmental noise exposure on the basis of estimates of noise annoyance (WHO, 2011).

The most significant effects of environmental noise on health come in the form of annoyance and sleep disturbance. Both are potential health stressors which can lead to and/or trigger more serious health problems. Figure 3.4 describes a pyramid of health effects which shows the graduation of severity of health-related impacts associated with chronic

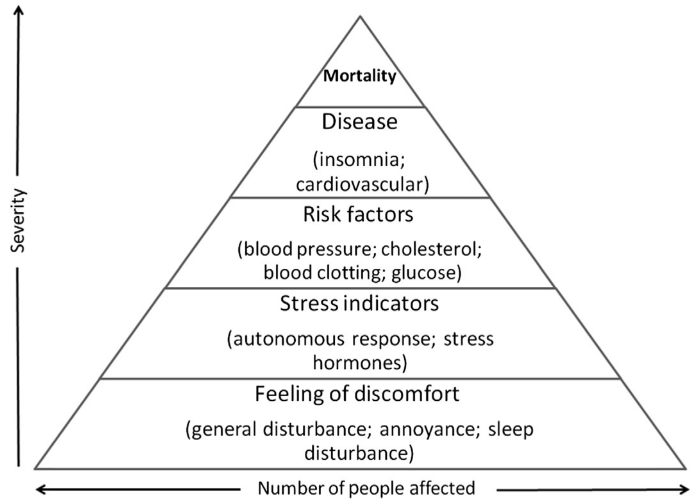

FIGURE 3.4 Pyramid of health effects of noise. *Source: Redrawn from Babisch (2002).*

long-term exposure to environmental noise; they range from feelings of discomfort through to enhanced risk of cardiovascular disease and ultimately mortality. Table 3.2 shows a summary of the main health effects of environmental noise exposure, the noise indicator used and the level above which health effects are considered detrimental for specific effects.

3.4 ENVIRONMENTAL NOISE AND ANNOYANCE

Annoyance response to transportation noise is considered to be quite a complex phenomenon. However, it is generally accepted to be the subjective discomfort associated with environmental noise exposure in humans and can be induced by individual perceptions of noisiness, disturbance to daily activities or a broadly negative feeling about the surrounding acoustic environment. One of the main characteristics affecting an individual's perception of sound as noise is its loudness or perceived intensity (Stansfeld and Matheson, 2003). As seen in Chapter 2, loudness comprises the intensity and tonal distribution of sound. In the scholarly literature, the evidence is mixed as to the importance of the duration and frequency components of sound as well as the number of sound events involved in determining annoyance.

It can be seen then that noise annoyance is subjective and this is primarily because, physiologically, individuals vary in their sensitivity to noise. For example, Raw and Griffiths (1988) found that self-reported sensitivity to noise is the most important variable for predicting ratings of annoyance. Put another way, different people may be more or less

TABLE 3.2 Summary of Effects and Threshold Levels for Effects of Nocturnal Noise Where There Is Sufficient[a] Evidence Available

Effect		Indicator	Threshold [dB]
Biological effects	Change in cardiovascular activity	–[b]	–[b]
	EEG awakening	$L_{Amax,inside}$	35
	Motility, onset of motility	$L_{Amax,inside}$	32
	Changes in duration of various stages of sleep, in sleep structure and fragmentation of sleep	$L_{Amax,inside}$	35
Sleep quality	Waking up in the night and/or too early in the morning	$L_{Amax,inside}$	42
	Prolongation of the sleep inception period, difficulty in getting to sleep	–[b]	–[b]
	Sleep fragmentation, reduced sleeping time	–[b]	–[b]
	Increased average motility when sleeping	$L_{night,outside}$	42
Well-being	Self-reported sleep disturbance	$L_{night,outside}$	42
	Use of somnifacient drugs and sedatives	$L_{night,outside}$	40
Medical conditions	Environmental insomnia[c]	$L_{night,outside}$	42

[a]*This means that a causal relation has been established between exposure to night noise and a health effect.*
[b]*Although the effect has been shown to occur or a plausible biological pathway could be constructed, indicators or threshold levels could not be determined.*
[c]*Environmental insomnia is the result of diagnosis by a medical professional while self-reported sleep disturbance is essentially the same, but reported in the context of a social survey.*
Source: WHO (2009).

annoyed by the same sound intensity. Thus, non-acoustic factors such as age, socio-economic characteristics and fear of noise have been found to play a major role in determining individual reactions to noise in the form of annoyance scores (Miedema and Vos, 1999, 2003; van Kamp et al., 2004). For example, after controlling for noise level, Fields (1992) found that 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. Indeed, it is estimated that only 33% of individual noise annoyance is accounted for by acoustic parameters (Guarinoni et al., 2012). The WHO report on the *Burden of Disease from Environmental Noise* concludes that one in three individuals in Europe is annoyed during the daytime. It is estimated that around 57 million people (12% of the population) in 25 EU countries are annoyed by road traffic noise with approximately 24 million (42%) of those being severely annoyed. In addition, rail traffic noise is estimated to cause annoyance in about 5.5 million people (1% of the European population), 2 million of who are severely annoyed (den Boer and Schroten, 2007).

As indicated earlier, noise annoyance is generally associated with the 'indirect' reaction chain in the human organism which is closely related to the initiation of emotional stress (i.e. cortical perception). Indeed, research studies have shown that individuals annoyed by noise tend to experience a series of negative emotions including anger, disappointment, unhappiness, withdrawal, distraction, anxiety, exhaustion and even depression (Fidell et al., 1991; Fields, 1998; Miedema, 2002; WHO, 2011). Thus, environmental noise has negative impacts on a person's quality of life and often forces unwanted alterations in the everyday behaviour of individuals. Examples include preventing residents from using residential areas such as balconies and common areas due to excessive noise levels as well as the shutting of windows in homes to prevent noise immission (Berglund et al., 1999). According to Stansfeld and Matheson (2003), conversation, watching television and listening to the radio are the activities most disturbed by aircraft noise, while traffic noise is often most disturbing for sleep but similarly affects everyday behaviour negatively.

Overall, road traffic noise is responsible for causing the greatest levels of annoyance. Figure 3.5 shows results from a longitudinal study from the Netherlands where residents reported road traffic noise as being responsible for the greatest volume of people highly annoyed while noise from

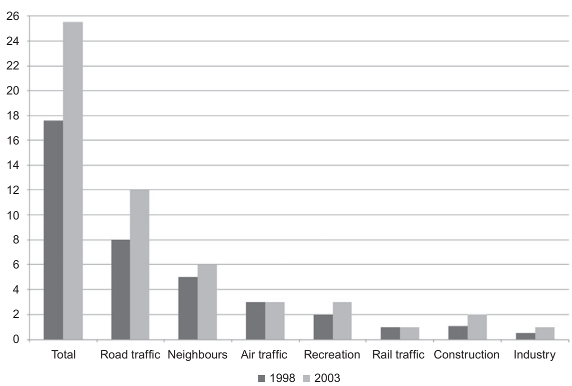

FIGURE 3.5 Percentage of the population highly annoyed by noise during sleep in the Netherlands. *Source: Adapted from WHO (2009).*

industry is the least. It is interesting to note also that the general trend is for a significant increase in annoyance from 1998 to 2003 and this trend holds for nearly all noise sources. These results generalise across Europe and imply that the problem of environmental noise is disimproving considerably over time. Of the various transport modes, rail is responsible for the least volume of annoyance in the general population; road-based modes account for the most. Indeed, it has been shown repeatedly in attitudinal studies that the degree of noise annoyance depends on the mode of transport being considered. At the same average noise level, the percentage of individuals highly annoyed increases from least to most in the following order: rail traffic noise, road traffic noise and aircraft noise. This relationship has been shown in studies by Miedema (2004) among others and has led to the introduction of a rail bonus in legislation in some countries (e.g. Germany) where the average rail traffic noise level may be 5 dB(A) higher than other traffic modes because of its lesser impact on annoyance (Basner et al., 2011). Indeed, a recent study of annoyance due to mixed transportation noise in Hong Kong found that when both road and rail noise are present, road traffic noise induces annoyance, while rail noise has the opposite effect (Lam et al., 2009). Rather interestingly, the same study found that perceived noisiness is a better predictor of noise annoyance than the actual noise exposure level.

The standard approach by which noise annoyance is assessed at the population level is through an attitudinal questionnaire. The International Commission on Biological Effects of Noise (ICBEN) and International Organisation for Standardisation (ISO) have made significant efforts to standardise the use of questions in noise annoyance surveys. They introduced a standard 11-point numerical scale as well as a 5-point semantic scale (see Figure 3.6). As well as this, Fields et al. (2001) have provided additional clarification for the conduct of noise reaction questionnaire surveys for

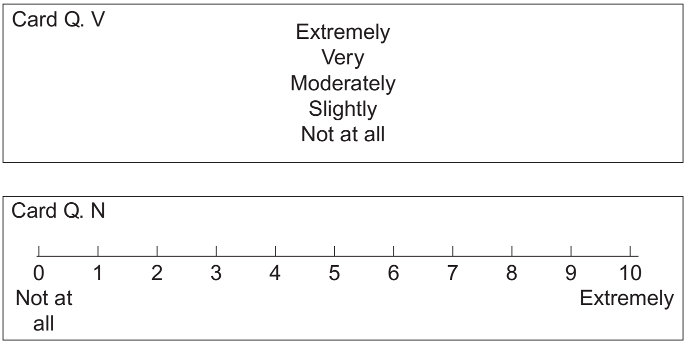

FIGURE 3.6 Answer cards for verbal (V) and numeric scale (N) noise annoyance questions. *Source: Fields et al. (2001).*

research purposes to ensure standardisation and comparison across studies. They recommend that noise reaction questions consist of one verbal answer scale question (V) and one numeric answer scale question (N) as follows:

> Q.V: Thinking about the last (..12 months or so..), when you are here at home, how much does noise from (..noise source..) bother, disturb, or annoy you; Extremely, Very, Moderately, Slightly or Not at all?
>
> Q.N: Next is a zero to ten opinion scale for how much (..source..) noise bothers, disturbs or annoys you when you are here at home. If you are not at all annoyed choose zero, if you are extremely annoyed choose ten, if you are somewhere in between choose a number between zero and ten. Thinking about the last (..12 months or so..), what number from zero to ten best shows how much you are bothered, disturbed, or annoyed by (..source..) noise?

If the questions are interviewer-administered, then respondents choose their answers from show cards provided to them based on the previously mentioned standardised scale (Figure 3.6).

Generally, studies that attempt to calculate noise annoyance do so on the basis of the proportion of the population that cite being 'annoyed' or 'highly annoyed' by environmental noise. Recently, the WHO has endorsed the use of 'highly annoyed' as the key reference condition for assessing potential health effects in the general population. Given that a number of noise reaction surveys have assessed response to noise using a range of different categories, it is often necessary to standardise various studies on a 0–100 scale to ensure comparability between studies (WHO, 2011).

The WHO (2011) have recently presented a methodology for estimating the prevalence of noise annoyance by combining existing noise exposure data with exposure–response relationships for noise annoyance that were determined in previous studies. Using evidence relating to burden of disease from other studies, they calculated the DW across the population of people 'highly annoyed' by noise at 0.02 (2%) albeit they acknowledge a potential DW range of anything from 1% to 12%. Although the methodology used is fairly crude, it is a pragmatic starting point for assessing the disease burden of environmental noise as a result of annoyance.

3.5 ENVIRONMENTAL NOISE AND SLEEP DISTURBANCE

It is now well established in the literature that excessive environmental noise disturbs sleep. If the disturbance is at a level that is severe enough, it can lead to sleep deprivation which can seriously affect the physical and mental health of an individual. The WHO (2009) estimate that 90,300 DALYs in populations greater than 50,000 are lost to sleep disturbance as a result of environmental noise exposure in the EU. No similar quantification has been applied in other jurisdictions throughout the world although localised (often city-specific) research investigating the link between noise exposure and sleep disturbance has indeed been completed beyond the EU.

Sleep disturbance is considered to be part of the extra-auditory effect of noise. The processing of auditory information involves a complex network of brain structures. The organ of Corti, which is located in the cochlea, is the receptive organ for audition (Pirrera et al., 2010). It is responsible for sending auditory information to the brain via the cochlear nerve. Input into the auditory area of the brain through the auditory pathways is prolonged by inputs reaching the brain as well as the cortical area and the descending pathways of the autonomic functions. Indeed, it has been established that individuals can experience autonomic responses to noise at low levels that do not lead to wakefulness (Muzet, 2007). As a result, an individual who is sleeping will still respond physiologically to noise stimuli from the surrounding environment even though the exact extent of the noise sensitivity of each individual is often dependent on several factors and can vary considerably.

Sleep disturbance can be quantified objectively by the number and duration of nocturnal awakenings, the number of sleep stage changes and modifications in their amounts. Subjectively, it can also be measured through questionnaires distributed to subjects on the morning after a night's sleep. Physiologically, sleep can be monitored using a sleep polygraph which records electroencephalography (EEG) and eye movements, while muscle tone is measured by means of electrodes (Carter, 1996). This method yields overnight measures of total sleep time, sleep efficiency and per cent of total time in the various sleep stages. Arousals and awakenings, whether they occur naturally or as a response to a noise event, can also be derived from a sleep polygraph. Indeed, it is also possible to detect whole-body movements and arm movements from accelerometers as an indicator of sleep disturbance (see Ohrstrom et al., 1988), while wrist movements have also been used in similar studies (Horne et al., 1994). From this, it is possible to deduce that excessive environmental noise exposure can significantly disturb sleep in the form of arousals, awakenings and in reducing the amount of time an individual spends in the deep sleep stages. These deep sleep stages – slow wave sleep (SWS) and rapid eye movement (REM) – are considered to be particularly important for physical recuperation in humans with SWS, in particular, acting as an energy restoration state for the sleeping body (Muzet, 2007). Carter's (1996) detailed review has shown that excessive exposure to noise during the night tends to reduce the amount of SWS. Indeed, a series of more recent studies focusing on the effects of aircraft-noise events on sleep structure showed that an increase in aircraft-noise events was associated with a decrease in SWS and increased awakening frequency in study subjects (Basner and Samel, 2005; Basner et al., 2006). Even earlier research has reported that REM sleep rhythmicity may also be affected by environmental noise (Naitoh et al., 1975). Research conducted by Ohrstrom and Skanberg (2004) has shown that sleep quality at home is reduced after exposure to traffic noise when compared to a quiet reference night. In terms of prevention and abatement, research has shown that if the indoor noise level is reduced, the amount of REM sleep and SWS can be increased considerably (Vallet et al., 1983).

In the early 1970s and 1980s, much of the research investigating the relationship between noise and sleep was at an early stage. There is now a significant body of work with consistent results, demonstrating the negative impacts of environmental noise on sleep structure. To take only one example, a recent study analysed the effects of train noise and vibration on human heart rate during sleep in Gothenburg, Sweden (Croy et al., 2013). The study had 24 participants each of whom spent six consecutive nights in a sleep laboratory – one habituation, one control and four experimental nights. For the experimental nights, 20 or 36 trains with low-vibration or high-vibration characteristics were presented to the subjects. The results found that exposure led to a statistically significant change of heart rate within 1 min of exposure to train noise and cardiac responses tended to be higher in the high-vibration than in the low-vibration condition. The results show that the human physiology reacts almost instantly to noise exposure during sleep. The authors concluded that train noise provokes heart rate accelerations during sleep which may affect the cardiovascular functioning of persons living close to railways in the long term. Similar results have been found in related studies. A recent review of the available evidence found a clear association between aircraft-noise events and sleep disturbance (Perron et al., 2012). The disturbances varied across studies but generally included awakenings, decreased SWS time and the increased use of sleep medication for noise-exposed subjects.

While environmental noise is an acute problem during the night-time period, it is also disturbing to sleep during the daytime period. Given that a significant proportion of the total workforce may be involved in shift work during the night and tend to sleep during the day, especially in the vicinity of airports and hospitals, noise-induced sleep disturbance can also be a daytime phenomenon. Indeed, this is an issue which is often neglected by environmental and public health officials. For example, the recent WHO report (2009) somewhat underestimates the extent of sleep disturbance from environmental noise because it only considers healthy life years lost to night-time sleep disturbance. The report does indeed recognise this as a problem, but further research is needed in the future assessing the extent of daytime sleep disturbance among populations.

Noise-induced sleep disturbance can vary for different modes of transport (road, rail, air) or modes in combination. In a recent laboratory-based study in Germany, 72 subjects (32 males) were studied for 11 consecutive nights with 0, 40, 80 and 120 noise events employed in a balanced design in terms of number of noise events, maximum sound pressure level and equivalent noise load (Basner et al., 2011). The results revealed that road traffic noise was responsible for the most significant changes in sleep structure and continuity despite the fact that subjects considered air and rail more disturbing subjectively; cortical and cardiac responses during sleep were lower for air compared to road and rail traffic. The difference between subjective attitudinal and objective physiological results associated with the various modes was attributed to road traffic noise events being too short to be consciously perceived by the subjects that had awoken in response to the noise events. An interesting aspect of the study was that the authors asked subjects to complete morning questionnaires to subjectively assess their previous night's sleep. They found that despite subjects being in an unconscious state for most of the night, they were able to distinguish not only between nights with and without noise but also between nights with low and high degrees of traffic noise exposure, indicating that morning questionnaires might be a more robust method of assessing traffic noise effects on sleep than previously thought.

One of the major issues related to environmental noise and sleep disturbance concerns how the noise might be characterised, specifically, whether the noise is considered to be continuous or intermittent. Laboratory studies using recorded intermittent and continuous traffic noise have demonstrated beyond any reasonable doubt that human subjects are disturbed more by intermittent noise than by continuous noise (Ohrstrom and Rylander, 1982). This is discussed further in Chapter 6. In Ohrstrom and Rylander's study, subjective sleep quality, mood and performance on reaction time (RT) tasks were all impaired by exposure to intermittent environmental noise at night, while continuous noise had a considerably less impact on sleep quality and no impact at all on mood or task performance. In another study, it was found that intermittent noises with peak noise levels above 45 dB(A) can increase the time taken to fall asleep by up to 20 min (Ohrstrom, 1993). And yet, for public health purposes noise continues to be evaluated during the night-time with continuous equivalent noise level indicators such as L_{eq}, L_{den} and L_{night} which, despite adding a night-time penalty (in the case of L_{night}), tend to smooth out intermittent noise events, thereby underestimating the magnitude of the health impact in terms of disturbance. Indeed, even as far back as the 1970s, Vernet (1979) found a low correlation between L_{eq} and the number of sleep disturbances for people exposed to road and rail traffic noise; by way of comparison, the study found a strong correlation between the number of disturbances and sleep stage changes with the peak noise level (L_{peak}) and number of noise events. This implies that it would be useful for relevant public authorities to use a noise disturbance indicator that accounts for intermittent noise in its equation if appropriate assessment of the sleep disturbance associated with night-time environmental noise exposure is to be achieved.

The reason why sleep disturbance is such an important issue in environmental noise studies relates to the fact that a reduction in sleep quality is associated with an array of secondary impacts – ‘after-effects’ – which are generally felt the day after disturbance has occurred. They encompass a broad range of psychological and physiological changes that may be evident in an individual including fatigue, low work capacity, reduced cognitive performance, changes in daytime behaviour as well as mood changes and associated negative emotions (Murphy et al., 2009). Tiredness is perhaps the most obvious impact of night-time exposure to noise and sleep disturbance. A number of studies have highlighted that individuals report increased feelings of fatigue after excessive night-time environmental noise exposure (Ohrstrom, 1995). Change in mood is another frequently reported after-effect. For example, in a laboratory-based study, Skanberg and Ohrstom (2006) found that subjects tended to have a better mood during quiet reference nights when compared with noisy nights. Moreover, Pirrera et al. (2010) have pointed out that there seems to be decent evidence to suggest that while sleep disturbance generally has negative effects on mood, intermittent traffic noise causes larger mood effects than continuous noise. Aside from mood, Stansfeld and Matheson (2003) point out that community surveys have found high percentages of people reporting ‘headaches’, ‘restless nights’ and ‘being tense and edgy’ in high noise areas.

Performance tasks have also been linked to the after-effects of sleep disturbance from environmental noise. Studies assessing the link between environmental noise, disturbed sleep and performance are usually examined through tests of RTs. A number of studies have shown that when RT tasks from the evening before a noisy night are compared with those from the morning after, longer RTs and a decrease in performance were found (Ohrstrom, 1995; Ohrstrom and Rylander, 1990). Marks and Griefahn’s (2007) study demonstrated that subjects tended to have longer RTs after noisy nights when compared to quiet nights, while Griefahn and Gros (1986) found higher RTs together with more errors (for men and older subjects) following noisy rather than quiet nights.

BOX 3.2

ENVIRONMENTAL NOISE AND SLEEP IN RATS

In a 2005 study, 29 male rats were exposed to environmental noise for 9 consecutive days in a laboratory setting (Rabat et al., 2005). The study sought to determine the effect of chronic noise exposure on sleep and to evaluate inter-individual vulnerability of sleep to environmental noise. The researchers monitored the sleep states of the rats by EEG recording and chronically implanted cortical electrodes. Audio software was used to translate all the noise frequencies from the human to the rat audiogram. Environmental noise exposure comprised background noise of 70 dB(A) as well as several unpredictable noise events. The results showed that following 9 days of exposure, there was an increase in wakefulness amounting to 16 h when compared to a controlled environment of 40 dB(A). In addition, the results showed that environmental noise exposure disturbs both SWS and paradoxical sleep (PS); after 9 days exposure rats lost about 1.1 and 0.75 h/day of SWS and PS, respectively. Rather interestingly, the study also revealed that rats do not habituate to the situation even after exposure ends and that chronic exposure to an environmental noise permanently disturbs sleep parameters in rats. The research has potential insights for the relationship between environmental noise and sleep in humans.

3.6 ENVIRONMENTAL NOISE AND CARDIOVASCULAR DISEASE

3.6.1 Hypertension

It is now well known that short-tem exposure to environmental noise is a stressor that activates the sympathetic and endocrine system. This may lead to acute changes in BP and heart rate as well as elevated levels of stress hormones in the body. Over the last two decades, a series of studies have produced results which suggest that transportation noise is associated with negative cardiovascular effects (Babisch, 2002). In particular, the evidence demonstrating a link between transportation noise and ischaemic heart disease (IHD) has increased considerably (Babisch, 2011). This is related to evidence which has emerged, suggesting that noise exposure increases the risk of hypertension and arteriosclerosis (a thickening or hardening of the arteries).

Studies investigating the relationship between environmental noise and hypertension have tended to focus on either aircraft or road noise exposure relationships, and the results emerging have not generally been consistent. According to Babisch (2006), this is most likely due to problems associated with how individual studies have been designed. However, since 2006, a considerable volume of additional evidence has emerged, suggesting a more definitive link between noise and hypertension (Davies and Kamp, 2012). Barregard et al. (2009) have recently examined physician-diagnosed hypertension in a cohort of 1953 adults. When road traffic noise, age, sex, heredity and body mass index were controlled for in logistic regression models as well as allowing for >10 years of latency, the odds ratio for hypertension was 1.9 (95% CI 1.1–3.5) in the highest noise category (56–70 dBA) and 3.8 (95% CI 1.6–9.0) in men. The study showed a positive association between residential road traffic noise and hypertension, indicating that individuals exposed to high levels of environmental noise are 1.9 times more likely to suffer from hypertension than non-exposed subjects (with males 3.8 times more likely). Similar results overall were found by Bluhm et al. (2007) among a sample of 667 adults in a municipality north of Stockholm although, conversely, their results found that women were more likely to suffer from hypertension due to higher noise exposure than men, indicating an inconsistency in results from different studies. The HYENA (hypertension and exposure to noise near airports) study provided interesting data (4861 respondents) on the effects of aircraft and/or road traffic noise in a study around six major European airports. It uncovered statistically significant exposure–response relationships between night-time aircraft as well as average daily road traffic noise exposure and risk of hypertension when adjustment was made for major confounders (Jarup et al., 2008). The study found a significant increase in risk of hypertension per 10 dB increase (adjusted) in road traffic noise; a more pronounced dose–response relationship was evident for men.

Babisch and van Kamp (2009) have recently summarised the evidence linking aircraft noise and hypertension. They conclude that there is indeed sufficient evidence for a positive relationship between aircraft noise and high BP but that the exact magnitude of the effect is still uncertain at present. Interestingly, they found that the effects were more pronounced when subjective measurements of high BP were considered, indicating the possibility of over reporting when subjective indicators are being utilised. Selander et al. (2009), using a subset of the HYENA data (439 subjects), found elevated morning cortisol levels in relation to aircraft noise at night, but only for women, and notably only those who were employed. Niemann et al.'s (2006) study of eight European cities found a statistically significant relationship between road traffic noise and hypertension. Rather importantly, their results show that the effect of severe noise exposure was evident in the respiratory system as well as the cardiovascular system. This was particularly the case for children where a close relationship emerged between traffic noise exposure and disorders of the respiratory system in children.

In the literature, the evidence base is considerably stronger for aircraft noise than for road traffic noise which continues to be somewhat variable. For example, a recent study in Sweden using 25,851 subjects found no association between environmental noise from roadways (assessed as traffic volume) and self-reported hypertension (Eriksson et al., 2012). However, the study found an increased risk for subjects exposed to railway noise greater than 50 dB(A) with a prevalence odds ratio of 1.55. This is quite a surprising result given that railways have traditionally been seen as less of an environmental noise risk especially in Europe. Overall, the body of evidence suggests an association between noise exposure and risk of hypertension although a direct causal link is yet to be fully established.

3.6.2 Ischaemic Heart Disease

As mentioned already, exposure to noise affects the sympathetic and endocrine system resulting in acute physiological responses such as heart rate, BP, stress hormones and electrocardiogram (ECG) changes (Babisch, 2011). In fact, the long-term effects of chronic noise exposure at high noise levels have been studied in animals with results showing permanent vascular changes and alterations of the heart muscle indicating a greater risk of cardiovascular mortality (Ising et al., 1979). In research studies, the relationship between noise and prevalence of IHD for cross-sectional studies is generally assessed by cyclical symptoms of angina pectoris, myocardial infarction (MI) or ECG abnormalities or from self-reported questionnaires regarding doctor-diagnosed heart attack (Babisch, 2006). For longitudinal studies, IHD incidence is assessed using hospital records, ECG measurements or clinical interviews (WHO, 2009).

The WHO (2009) has recently concluded that there is sufficient evidence to suggest a relationship between excessive daytime noise exposure and increased cardiovascular risk. However, the increase in risk is only evident in areas with a daytime average sound pressure level above 60 dB(A). Moreover, the evidence linking road traffic noise with IHD is stronger than that for aircraft noise due to a lack of research investigating the association between aircraft noise and cardiovascular health (WHO, 2011). However, the same document – *Night Noise Guidelines for Europe* – has also concluded that, with respect to night noise, only limited evidence of increased risk of cardiovascular disease is evident for night noise levels above 55 dB(A). As Babisch (2011) has pointed out, this does not mean that a link does not exist but that the available evidence base is limited because there are an insufficient number of studies completed where the exposure of the bedroom is explicitly related to the night noise level. The vast majority of studies that have been completed have been on the link between daytime noise and cardiovascular health and have simply inferred relations for night noise from daytime studies which is obviously not ideal in terms of determining a definitive relationship during night-time. As a result, additional research is needed explicitly investigating night noise levels and bedroom exposure.

Despite these caveats, Babisch et al. (2005) found evidence of a link between traffic noise exposure (using noise maps) greater than 60 dB(A) and increased risk of MI – commonly known as heart attack – for subjects in Berlin. Their research revealed that men were susceptible to greater risk than women who demonstrated no increased risk from chronic traffic noise exposure. Additional research by Babisch et al. (2013) suggests that noise is an effect modifier in that it may be an environmental stressor which increases the risk of cardiovascular outcomes in exposed subjects. A similar and more recent study in Switzerland analysing 15,532 deaths from MI found that mortality increased with increasing level and duration of aircraft-noise exposure with individuals living in the same location for more than 15 years at greater risk (Huss et al., 2010).

In addition, a recent study was conducted investigating in the relationship between traffic noise and incidence of stroke in Denmark (Sørensen et al., 2011). In total, 1881 cases of Danish adults aged between 50 and 64 living in the Copenhagen or Arhus area were analysed. The results revealed a relationship which suggested that the incidence of stroke increased by 14% for every 10 dB(A) increase of traffic noise (L_{den}). More specifically, they showed that residential traffic noise was particularly associated with a higher risk of stroke among people older than 64.5 years old.

Occupational noise is also associated with increased cardiovascular risk. A recent study of 6307 workers in the United States concluded that self-reported occupational noise is strongly associated with prevalence of coronary heart disease (CHD) including being associated with a two- to threefold increased prevalence of angina pectoris, MI, CHD and hypertension (Gan et al., 2011).

3.7 ENVIRONMENTAL NOISE AND COGNITIVE IMPAIRMENT IN CHILDREN

Over the last two decades, there has been a major increase in the number of studies investigating the effect of environmental noise on children. This is largely related to the fact that early evidence indicated that children might be particularly susceptible to the risks associated with excessive environmental noise exposure. According to the WHO (2009), risk groups are people who may be either sensitive to or more exposed to environmental noise exposure or both. Children are considered to be one of those groups where environmental noise has more significant health impacts relative to the rest of the general population. While the WHO (2009, p. 75) have stated that children do not appear to be at any additional risk than the rest of the population with respect to cardiovascular outcomes, the long-term impacts of exposure at a young age have yet to be studied and it may well be that there are longer term impacts of chronic exposure during childhood particularly within the context of cognitive development.

The most consistent impact on children exposed to excessive noise levels is in terms of cognitive impairments, motivation and annoyance. Studies that have considered the effect of noise on children have tended to focus on noise in schools rather than at home. As such, there is now a useful body of literature highlighting the impacts of noise exposure on child cognition and learning. Studies have found that tasks involving central processing and language comprehension, such as reading, attention span, problem solving and memory, appear to be most affected by exposure to noise (Evans and Maxwell, 1997; Stansfeld and Matheson, 2003). In other words, the effects of environmental noise have been shown fairly uniformly across the entire range of cognitive functions.

Hygge et al. (2002) found that aircraft noise had a significant and negative impact on the reading ability of schoolchildren. In a different study of 1358 children aged between 12 and 14 years old, 10 experiments were used to test for recall and recognition of a text in quiet and noisy conditions for various transportation noise sources including road, rail, aircraft and combinations of these with one or other source dominating (Hygge, 2003). Overall, the results found a strong and negative noise effect on recall and a smaller but still significant effect on recognition. Similarly, a study examining teacher's reports of their students showed that noise-exposed children have greater difficulty concentrating than children from quieter schools (Ko, 1981), while research in the United States found a link between environmental noise exposure and reduced visual attention in children (Hambrick-Dixon, 1988). In a recent study of London primary schoolchildren (7–12 years old), external noise was found to have a significant negative impact on performance with the effect being somewhat greater for the older children included in the study (Shield and Dockrell, 2008).

Somewhat worrying is the emerging link between transportation noise exposure and children's mental health. It is notable that only a small number of studies have attempted to examine the link between environmental noise and psychological disorders in children. As a result, the present nature of the relationship is tentative and in need of further confirmation. However, a recent study – the UK RANCH[2] project – examined the link by conducting a cross-national, cross-sectional study assessing 2844 pupils (aged 9–10) from 89 schools around three major airports in the Netherlands, Spain and the United Kingdom (Stansfeld et al., 2009). Mental health issues explored included emotional problems, conduct disorder, hyperactivity, peer problems and prosocial behaviour.[3] The results revealed that aircraft-noise exposure was significantly associated with high levels of hyperactivity, while road traffic noise was significantly associated with higher levels of misconduct after adjusting for socioeconomic factors. Indeed, similar results for hyperactivity were confirmed in a more recent study in Germany (Tiesler et al., 2013). In the first longitudinal study of the effects aircraft-noise exposure on children, a 6-year follow-up of the RANCH study confirmed many of the results of the original study including that aircraft-noise exposure at school might impair reading comprehension and lead to an increase in noise annoyance in children.

A number of studies have also identified an association between chronic exposure to aircraft noise and reduced motivation in children (Evans et al., 2001). However, the results are certainly not conclusive and demonstrate some inconsistency which means that further research is needed in the area. For example, in a Los Angeles study of the effects of aircraft noise on children's cognition and motivation, the authors found that children exposed to chronic aircraft noise were more likely to give up on a difficult puzzle than children not suffering from chronic noise exposure (Cohen et al., 1980). In a 1-year follow-up to the Los Angeles study, which included the same students, the finding that noise-exposed children were more likely to give up on a difficult puzzle was not replicated demonstrating inconsistency in the results (Cohen et al., 1981). Similarly in a Munich study, children from noisy communities were found to give up more easily on an insoluble puzzle than children from quiet communities (Evans et al., 1995). Rather interestingly, that study also found an association between noise-exposed children and reduced quality of life scores on a standardised index.

[2]Road traffic noise and Aircraft Noise exposure and children's Cognition and Health (RANCH).

[3]Prosocial behaviour refers to voluntary behaviour intended to benefit another such as helping, sharing, donating, co-operating and volunteering, generally demonstrating altruism and solidarity to others.

BOX 3.3

AIRCRAFT NOISE AND COGNITIVE PERFORMANCE IN SCHOOLCHILDREN

A 2002 study in Munich, Germany assessed how children's reading was affected by changes in ambient noise levels caused by modified airport operations (Hygge et al., 2002). At that time, the simultaneous opening and closing of the new and old airports at separate locations provided a unique opportunity to conduct a study on the effects of aircraft noise on children. Children near both sites were recruited into aircraft-noise groups and control groups with no aircraft noise (controlling for economic status). A total of 326 children took part in data collection experiments before and after the switchover of airports. After the switchover, the study found that long-term memory and reading were impaired in the noise group at the new airport but it improved significantly in the group that was formerly exposed to noise at the old airport. Not only that but short-term memory also improved for the group formerly exposed to noise at the old airport. Meanwhile, at the new airport speech perception was impaired in the group newly exposed to environmental noise. The study concluded that aircraft noise has clear cognitive impacts on children.

3.8 ENVIRONMENTAL NOISE AND TINNITUS

Tinnitus is defined as the sensation of sound in the absence of an external sound source and is often associated with partial hearing loss. It can cause sleep disturbance, cognitive effects, anxiety, psychological distress, depression communication problems, frustration, irritability, tension, inability to work, reduced efficiency and restricted participation in social life (WHO, 2011). Excessive exposure to noise is generally what causes tinnitus. Environmental noise from social/leisure noise such as personal music players, gun shooting events, music concerts, sporting events and events using firecrackers is associated with tinnitus (WHO, 2011). Somewhere between 50% and 70% of patients with chronic noise trauma and 12–50% of patients with noise-induced hearing loss report having tinnitus (Sindhusake et al., 2004). Population-based research investigating the relationship between environmental noise exposure and tinnitus is rare in the academic literature, but it is generally accepted that it is a risk when noise exposure is high.

3.9 THE SPECIAL CASE OF LOW-FREQUENCY NOISE

The relationship between low-frequency environmental noise exposure and health-related problems has been less of a focus in the academic literature than noise in the traditional A-weighted bands. Although exact definitions are somewhat difficult to pinpoint, low-frequency noise (LFN) is generally taken to be noise from 20 to 200 Hz with noise below 20 Hz being referred to as infrasound (Leventhall, 2004). Most walls in buildings tend to be deficient in attenuating noise in the low-frequency region (Leventhall, 2003), meaning that residential exposure to LFN can pose an even greater problem than noise in the normal frequency range.

The WHO recognise the special place of LFN as an environmental problem suggesting that 'low-frequency components in noise may increase the adverse effects considerably' (Berglund et al., 1999, p. 61). Persson and Bjorkman (1988) and Persson et al. (1990) found that dB(A) underestimates the level of annoyance for LFN. This, along with other related work, implies that noise at low frequencies is considered more annoying by individuals (Berglund et al., 1996; Broner, 1978; Pawlaczyk-Luszczynska et al., 2010). Moreover, related research has also found that LFN has a greater degree of 'unpleasantness' than noise in the A-weighted frequency bands (Inukai et al., 2000; Nakamura and Inukai, 1998). Exposure to LFN also causes sleep disturbance (Leventhall, 2003) and its associated secondary effects with the WHO (Berglund et al., 1999) noting that it 'can disturb rest and sleep even at low-sound levels'. Indeed, the work of Ising and Ising (2002) has demonstrated that LFN seriously impacts on the sleep quality of children. Moreover, Persson-Waye et al. (2002) have shown that adult exposure to low-frequency traffic noise is associated with greater degrees of fatigue and a negative mood.

Other research on LFN and health has indicated that it has an impact on peripheral task performance (Kyriakides and Leventhall, 1977), while more recent research has shown that it negatively affects demanding verbal tasks in the work environment (Persson-Waye et al., 2001). Ising and Ising (2002) demonstrated that compared to a control group, children exposed to LFN have significantly more problems with concentration and memory. In public surveys conducted to assess subjective well-being for individuals exposed to LFN, Møller and Lydolf (2002) found multiple self-reported health effects including disturbance when falling asleep, awakenings, frequent awareness of the noise, irritation and disturbance when reading. Other effects reported were insomnia, lack of concentration, headaches and palpitations. A laboratory study by Persson-Waye et al. (1997) showed that subjects exposed to LFN were less happy and had a poorer social

TABLE 3.3 Criteria for the Control of Annoyance due to Low-Frequency Noise

Sensitive Receiver		Range	Criteria L_{eq} [dB(C)]
Residential	Night-time or plant operation 24/7	Desirable	60
		Maximum	65
	Daytime or intermittent (1–2 h)	Desirable	65
		Maximum	70

Source: *Broner and Knight-Merz (2011).*

orientation. Moreover, Persson-Waye and Bengtsson's (2002) work suggests that LFN represents 44% of all noise complaints in Sweden.

To account for the additional annoyance likely to be experienced due to the presence of LFN, the overall A-weighted noise level (usually expressed in terms of L_{Aeq}) may be adjusted by a correction factor. For annoyance due to LFN, Broner and Knight-Merz (2011) propose simple criteria (Table 3.3): if the noise level is fluctuating by 5 dB(C), then a penalty of 5 dB(C) should be added, i.e., the criteria should be reduced. This is because annoyance is exacerbated due to the significant change in perceived loudness with change in sound pressure levels. A further procedure for the assessment of LFN is presented by Newman and McEwan (1980) who reference a British Gas Corporation criterion for specifying noise control for gas turbines. This involves a 60 dB limit in the 31.5 Hz octave band at the nearest dwelling. If there are distinguishable tonal or impulsive elements present in the noise source BS 4142 suggests applying a 5 dB correction factor to the L_{eq} value. However, ISO 1996-1 offers a more stringent and detailed approach: for tonal elements in the noise source, the correction should be 3–6 dB.

3.10 CONCLUSION

The broad conclusion that can be drawn from the evidence presented in this chapter is that environmental noise is quite a serious public health issue throughout the world. Much of the research that has been conducted on the health effects of noise in the last two decades has had Europe or the United States as its main geographic focus. However, the implications of the emerging body of evidence for public health policy throughout the world are significant. While the EU, in particular, is leading the way in terms of assessment and mitigation of excessive environmental noise exposure, it is important that other nations follow that lead in order to prevent noise pollution becoming an even more prominent public health issue.

Overall, the evidence suggests that environmental noise should be placed at the forefront of national and international health policies in order to prevent unnecessary adverse health impacts on the general population. This involves attempting to mitigate against the harmful effects of environmental noise on citizens. In this regard, the WHO (2009) have recently suggested that night-time noise levels above 40 dB(A) should be mitigated against to protect public health. This implies that policymakers should strive towards achieving levels below this figure. Indeed, Table 3.4 demonstrates that noise exposure even above 30 dB (A) is associated with a range of adverse health effects (see Table 3.4). If citizens are to be protected, it will require a long-term strategy that will need to incorporate the adoption of night-time noise limit values through legislation.

TABLE 3.4 Health Effects of Various Noise Levels in the General Population

Average Night Noise Level over a Year $L_{night,outside}$ [dB]	**Health Effects Observed in the Population**
Up to 30	Although individual sensitivities and circumstances may differ, it appears that up to this level no substantial biological effects are observed. $L_{night,outside}$ of 30 dB is equivalent to the no observed effect level (NOEL) for night noise.
30–40	A number of effects on sleep are observed from this range: body movements, awakening, self-reported sleep disturbance and arousals. The intensity of the effect depends on the nature of the source and the number of events. Vulnerable groups (for example, children, the chronically ill and the elderly) are more susceptible. However, even in the worst cases the effects seem modest. $L_{night,outside}$ of 40 dB is equivalent to the lowest observed adverse effect level (LOAEL) for night noise.
40–55	Adverse health effects are observed among the exposed population. Many people have to adapt their lives to cope with the noise at night. Vulnerable groups are more severely affected.
Above 55	The situation is considered increasingly dangerous for public health. Adverse health effects occur frequently, and a sizeable proportion of the population is highly annoyed and sleep disturbed. There is evidence that the risk of cardiovascular disease increases.

Source: WHO (2009, XVII)

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