

The health effects of environmental noise



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SUMMARY

Overview

The potential health risks of environmental noise are gaining increasing attention.

With increasing urban populations and changes in urban development, a growing number of people in Australia are being exposed to environmental noise.

The research literature has grown substantially, providing new insights into how people are being exposed to noise and potential health risks.

This review intends to inform noise policy and regulation in Australia by evaluating the evidence of the health effects of environmental noise. It also highlights specific areas for further research.

The review concludes that although the evidence is still emerging, it is sufficient to show that noise adversely affects health. Actions to reduce environmental noise exposure should be considered where feasible.

Scope of this review

This review updates and revises a 2004 enHealth Australia report on the non–auditory effects of environmental noise. It evaluates more than 200 research papers, publications and policies from January 1994 to March 2014.

It includes a systematic review of international evidence on the influence of environmental noise on sleep, cardiovascular disease and cognitive outcomes.

For each outcome, the review considers evidence for the relationship between levels of environmental noise exposure and health outcomes, the influence of different noise sources, and impact on vulnerable populations.

It considers annoyance as a mediating factor between environmental noise exposure and health outcomes, rather than a separate factor. The auditory impacts of noise are excluded as most of these studies are in the context of occupational noise.

Chapter 1 in this document defines noise and common noise measurements, and introduces the effects of noise on health.

Chapter 2 identifies sources of environmental noise and reviews current Australian regulatory approaches to managing community exposures. It draws on the European Union's experience in implementing its environmental directive. This framework allows for reliable and strategic noise mapping and action planning and may prove useful in an Australian context.

Chapters 3, 4 and 5 systematically review studies on the effect of noise on sleep disturbance, cardiovascular disease and cognition.

Chapter 6 includes discussion on the highest quality studies examining these health effects. It aims to give further guidance to assist regulatory authorities and public health professionals by providing insight into causal probability, identifying threshold boundaries for health effects and the magnitude of these effects.

Chapter 7 details the review's recommendations for policy review and further research, and actions for state health, environment and planning authorities.

The objectives and methodology for this review are further defined in appendix A.

Summary of findings

There is sufficient evidence of a causal relationship between environmental noise and both sleep disturbance and cardiovascular disease to warrant health based limits for residential land uses:

- During the night-time, an evidence based limit of 55 dB(A) at the facade using the $L_{eq,night}$, or similar metric and eight-hour night-time period is suggested.
- During the day-time, an evidence based limit of 60 dB(A) outside measured using the $L_{eq,day}$, or similar metric and a 16 hour day-time period is suggested.

There is some evidence that environmental noise is associated with poorer cognitive performance. However findings were mixed and this relationship requires further investigation.

It is plausible that aircraft, rail and road traffic noise have differential effects on sleep quality and cardiovascular health, but the evidence is not conclusive.

It is possible that health impacts may be greater among certain vulnerable groups, but further investigation is needed before making conclusions.

Research on the health impacts of environmental noise in the Australian context should be a priority. There is a particular lack of research on environmental noise exposure and health impacts in rural areas. Intervention studies examining the effects of change in noise exposure on changes in population health are also needed.

Key recommendations of this review

This review makes four overarching recommendations for measures to address the health impacts of environmental noise.

Recommendation 1: Recognise that environmental noise is a health risk

Policy

- consider this review when developing national environmental noise goals
- include noise as an important environmental health issue for strategic and local planning at a state and national level
- review the adequacy of existing health guidelines in state and territory legislation

Interventions

- promote awareness of the impacts of environmental noise on health

Information

- inform communities and stakeholders of national and international standards and guidelines

Recommendation 2: Promote measures to reduce environmental noise and associated health impacts

Policy

- review consistency of existing legislation across all levels of government

Interventions

- review noise arising from transportation, including noise criteria for areas adjacent to transport infrastructure
- promote noise mitigation measures such as acoustic barriers or noise insulation in residential buildings and licensing controls to limit noise impacts

Information

- develop a national environmental noise reduction education program, which could be supplemented with additional state-specific campaigns

Recommendation 3: Address environmental noise in planning and development activities

Policy

- include environmental noise in the health impact assessment of proposed developments, where warranted
- determine baseline environmental noise levels to inform planning actions (noise mapping)
- review noise control practices and how to further integrate noise control into planning processes, for all levels of government (with attention to future noise research findings)
- foster national consistency on guidelines to minimise or prevent environmental noise from developments, limiting noise from major sources, and methods to set noise limits

Interventions

- carry out baseline monitoring of environmental noise levels to ascertain existing ambient levels across a broad range of populations and land use areas
- apply appropriate controls where noise is known to have an effect
- develop national and state action plans for both the long and short term to integrate planning and research at all levels of government
- develop guidelines for noise sensitive developments for layout, design and construction for planning authorities

Information

- develop state information strategies to keep communities informed of advances in measures to improve noise

Recommendation 4: Foster research to support policymaking and action

Policy

- identify factors giving rise to sensitivity to noise and vulnerability to non-auditory health effects to inform environmental, planning and health policies

Interventions

- conduct a rigorous evaluation of national, state and city population exposures to each major noise source
- support noise mapping projects to determine community noise exposures to each major noise source that could be used to inform land use planning or burden of disease studies
- conduct evaluations of noise reduction schemes on community health
- promote further research on the effects of noise on learning performance in children, sleep disturbance, annoyance and cardiovascular health and mental wellbeing to establish threshold levels

Information

- translate research findings into useful information for community and relevant stakeholders

Oversight of this review

An expert advisory group oversaw this review and endorsed the final document. The group comprised experts in acoustics, environmental health, epidemiology, sleep medicine, urban studies and noise exposure, public health medicine and environmental noise regulation.

The group provided technical advice on the review's scope, content, conclusions and recommendations. The group also oversaw the process for commissioning evidence reviews including the scope, search strategy and criteria for high quality research and the revision of high quality papers and grading of evidence.

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This document updates the original enHealth document, *the Health Effects of Environmental Noise – Other Than Hearing Loss*, published in 2004.

1 SOUND, NOISE, HEARING AND HEALTH

1.1 Noise, environmental noise and health

Noise can be defined as unwanted sound. Environmental noise, or community noise, is defined by the World Health Organisation (WHO) as 'noise emitted from all sources except noise at the industrial workplace' (Berglund et al., 1999).

The main sources of community noise include: transport (road, rail and air traffic), industries, construction, public works, and the neighbourhood.

The potential health risks of environmental noise are gaining increasing attention. WHO defines health as 'a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity' (WHO, 1946). This broad definition enables us to consider not only the direct impacts environmental noise has on health, but also its impacts on sleep disturbance, cognitive effects and annoyance. In 2011, WHO quantified the burden of disease due to environmental noise exposure. Health end points included cardiovascular disease, cognitive impairment, sleep disturbance, tinnitus and annoyance. In one example of this, WHO estimates that at least 1 million healthy life years are lost every year from traffic-related noise in western Europe (WHO, 2011).

Table 1-1: Definitions and acronyms

Term	Definition
A-weighting i.e. dB(A)	A frequency weighting devised to attempt to take into account the fact that human response to sound is not equally sensitive to all frequencies
Amplitude	A measurement of the energy carried by a wave – the greater the amplitude of the wave, the higher the level of energy carried; for a sound wave, the greater the amplitude, the louder the sound
Audibility threshold	Also known as the absolute threshold of hearing, it is the minimum sound level across the frequency spectrum that an average ear with normal hearing can register with no other sound present
Broadband sound	When a sound is produced by a broad range of frequencies, it is generally called broadband (such as sound from a waterfall)
Decibel (dB)	A unit of measure used to express the level of sound, calculated as the logarithmic ratio of sound pressure level against a reference pressure
Environmental noise	A term to describe unwanted outdoor noise generated by human activity
Frequency (hertz, Hz)	The number of sound waves or cycles passing a given point per second; 1 cycle per second = 1 hertz (Hz)
Noise	Unwanted sound or an unwanted combination of sounds.
Presbycusis	Age-related hearing loss. The cumulative effect of ageing on hearing
Sound	An energy form that travels from a source in the form of waves or pressure fluctuations, transmitted through a medium and received by a receiver (e.g. human ear)
Sound frequency ranges	Infrasound <20 Hz Low-frequency sound 20 – 200 Hz Mid-frequency sound 200 – 2000 Hz High-frequency sound 2000 – 20,000 Hz
Sound intensity (I)	A measure of the sound power per unit area of a sound wave; alternatively, the product of the sound pressure and the particle velocity

Term	Definition
Sound power (watt, W)	A measure of the sonic energy per unit of time of a sound wave; alternatively called acoustic power; calculated by the sound intensity times the unit area of the wave; the total acoustic power emitted in all directions by the source
Sound pressure	A measure of the sound power at a given observer location; can be measured at the specific point by a single microphone or receiver
Sound pressure level (SPL)	A logarithmic measure of the sound pressure of a sound relative to a reference value, measured in decibels (dB) above a standard reference level using the formula $SPL = 10\log_{10}[p^2/p_{ref}^2]$ where p_{ref} is the reference pressure or 'zero' reference for airborne sound (20×10^{-6} Pascals)
Syscusiis	Lowering of the threshold of aural discomfort and pain
Unspecified noise	Noise for which study authors have not specified a frequency range or decibel level
Vibration	Vibration refers to the oscillating movement of any object and can be used to describe what a person feels
Tinnitus	The conscious perception of sound in the absence of an external sound
Tonal sound	Sound containing audible discrete frequencies

1.2 Basics of noise measurement

In scientific terms, sound is energy that travels from a source in the form of waves or pressure fluctuations. It is transmitted through a medium and picked up by the human ear or another receiver.

Sound has several important properties:

- level or amplitude (loudness) of sound – the sound pressure level (SPL) relative to a reference sound pressure level, which is measured in decibels (dB) using a logarithmic scale
- duration or time period – how sound is distributed over time (continuous, intermittent or impulsive)
- frequency (pitch) – the number of sound waves or cycles passing a given point per second; measured in cycles per second (1 cycle per second = 1 hertz (Hz)).

Humans can hear a wide range of sound frequencies, from 20 to 20 000 Hz and over a wide range of amplitudes, from a whisper to the point of pain.

Noise definitions vary slightly in different countries. In general, noise is classified in three broad frequency ranges:

- low frequency range: 20 – 200 Hz
- medium frequency range: 200 – 2,000 Hz
- high frequency range: 2,000 – 20,000 Hz.

Frequencies below 20 Hz are infrasonic. As the frequency below 200 Hz falls to about 16 Hz and less, the hearing sensation changes to a feeling of pressure.

Low frequency noise is part of urban background noise. Examples include noise from road vehicle and aircraft emissions, industrial and construction activities, ventilation and air-conditioning units, and compressors. Low frequency noise also occurs in nature. Examples include noise from wind or waves at a beach.

Very high frequencies (above 20,000 Hz) are ultrasonic and cannot be heard by the human ear.

Figure 1-1 gives examples of familiar sounds at their noise level dB(A). It shows that the risk of hearing loss depends on the noise level and length of exposure.

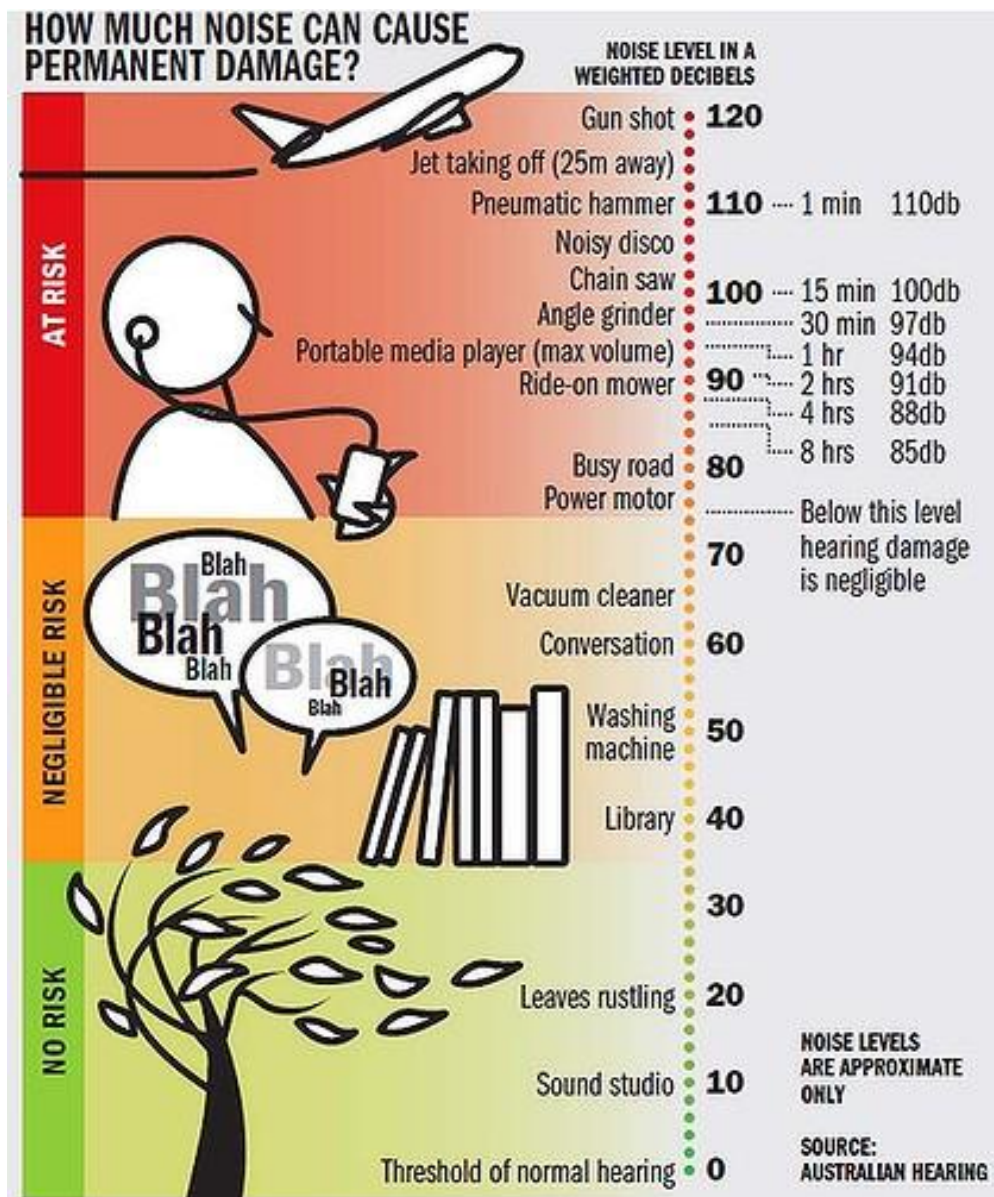


Figure 1-1: Noise levels of familiar sounds and the risk of hearing loss (Australian Hearing, 2014; image adapted by *The Sydney Morning Herald*, 2011).

Humans hear some frequencies more acutely than others and sound measurements are often filtered to reflect this sensitivity. The most common example is the 'A-weighting'. This focuses on the mid and high-range frequencies we hear and has less emphasis on low frequencies to which our hearing is less sensitive. However, it should be noted that although humans are less sensitive to low frequencies, that does not mean we should give less emphasis to low frequencies. Many complaints arise from low-frequency noise.

As sound is emitted from a source, it spreads in the air and its level decreases as it travels further. According to the WHO (1990) this attenuation is due to several factors:

- the distribution of acoustic energy over a geometrically expanding area with increasing distance
- sound absorption by the air
- interference with the ground surface
- physical barriers between noise sources and receivers
- meteorological factors such as wind, temperature gradients and humidity.

When interpreting acoustical data, different metrics are often used for different classifications or types of noise.

A knowledge of sound, noise and human response leads to a selection of noise descriptors, frequency and time weightings to describe and replicate human responses to sound and its impact. Table 1-2 lists common descriptors used to quantify the noise environment.

Table 1-2: Common noise descriptors

Descriptor	Definition
L_{Aeq,T}	The equivalent continuous A-weighted sound pressure level measured over a period T – that level of constant noise equivalent to the varying noise levels occurring over a measurement period T, often termed the energy-average noise level. It is often used to measure road and rail noise, industrial noise, noise from heating, ventilation and air conditioning and occupational noise exposure. Time periods can include L _{Aeq,night} and L _{Aeq,day} . Similarly, periods can vary from 1 minute to 24 hours and are recorded as L _{Aeq,1 min} and L _{Aeq,24 hr} *
L_{peak} (linear)	Used in setting hearing conservation limits for impulsive noise
L_{Ar,T}	The time average A-weighted sound pressure level of a sound source during a specified time interval, plus specified adjustments for tonal and impulsive character of the sound (time weighting may be 'F' or 'S' †)
L_{dn}	Day-night sound level is the equivalent A-weighted sound level during a 24-hour period with a 10 dB weighting applied to L _{Aeq} during the hours of 10pm to 7am to reflect greater annoyance experienced during night time
L_{den}	The day-evening-night level is the equivalent A-weighted sound level during a 24-hour period with a 5 dB weighting for evening and a 10 dB weighting for night. Day is 12 hours, the evening 4 hours and the night 8 hours and is determined over a year
L_{night}	The night-time noise indicator is the A-weighted long-term average sound level determined over all the nights of a year and in which the night is 8 hours. The definition of L _{night} does not include an addition of 10 dB
L_{ax}, L_{AE} or SEL	Sound exposure level of a discrete noise event is the instantaneous A-weighted sound pressure level integrated over the duration of the noise event and referenced to a duration of one second. SEL is used for measuring noise from individual pass-bys of transportation. A cumulative L _{Aeq} over a reference period can be determined from this. SEL is also sometimes used for sleep disturbance criteria
L_{Amax}	The maximum instantaneous sound pressure level measured on 'F' time weighting or 'S' time weighting

* Local regulatory requirements may define varying periods for L_{Aeq,T}.

† F and S are defined in relevant Australian Standards.

Descriptor	Definition
L_{An,T}	<p>The A-weighted sound pressure level obtained by using 'F' or 'S' time weighting that is equalled or exceeded for a percentage of the time interval considered. Common examples are:</p> <ul style="list-style-type: none"> • L_{A10,T}: the A-weighted sound pressure level which is exceeded 10% of the time; T, often used to represent the average of the maximum noise levels during a measurement period • L_{A90,T}: the A-weighted sound pressure level which is exceeded 90% of the time; T, often used to represent the average of minimum noise levels during a measurement period or the background noise level in the absence of the noise under investigation
N70	<p>Other noise descriptors are used in some circumstances. This includes N70 (number of aircraft events >70 dB(A) over any specified period), which is used to describe over-flight noise exposures. The 70 dB(A) sound level is chosen because an aircraft noise event of this, or louder, magnitude is likely to disturb conversation or interfere with listening to the radio or television inside a house with an open window</p>

1.3 Tranquillity, quiet areas and potential positive health effects of sound environments

The absence of unwanted sound (noise) is not necessarily quietness. In fact, natural background sounds in certain contexts can be seen as enjoyable or wanted. For example: wind rustling in trees, waves crashing on a beach, waterfalls and birds singing. Some human sounds may also be comforting, such as the burble of voices or the sound of children playing.

Tranquillity is a term used globally. It is defined as: 'the quality or state of being tranquil; calmness, serenity, a disposition free from stress or emotion and a state of peace and quiet'. It can also be defined as: 'a sense of calm or quietude'. It is often understood in terms of engagement with the natural environment (Jones, 2012).

Related concepts include soundscapes and quiet areas. Soundscape is a complementary concept to environmental noise management, where sound is seen as a resource to be managed. Soundscapes focus on sounds of preference rather than sounds that cause discomfort. The metric is listener-centred rather than an objective-based energy metric.

Quiet areas are referred to in the European Union's Environmental Noise Directive. These are defined for an urban agglomeration as 'an area which is not exposed to a value of L_{den}, or of another separate indicator greater than a certain value set by the member state, from any noise source' (European Union, 2002). This definition of quiet, put more simply, is 'not noisy'. The directive legislates for the identification and protection of quiet areas throughout the European Union.

The benefits of quiet or tranquil places are not usually considered in terms of health but rather in ideas of amenity, attractiveness, pleasantness, calmness, restfulness and restoration. While there are plausible grounds for considering some acoustic environments as conducive to health benefits, there is a lack of substantive evidence on the issue. This is an emerging field. Aiming to achieve tranquillity may encourage broader interest in managing the acoustic environment.

1.4 Theoretical models to account for how noise affects human response

Several theoretical models explain the complex relationship between noise and the human response to it. Some of these models are outlined below. However, a detailed discussion is outside the scope of this document.

1.4.1 The noise/stress concept and general stress model

The noise/stress concept (Babisch, 2002) considers noise in terms of its physiological response: a psychosocial stressor that stimulates the sympathetic and endocrine systems. Noise activates

the hypothalamo-pituitary-adrenal axis and the sympathetic-adrenal-medullary axis producing catecholamines and steroid hormones that affect metabolism. Changes in adrenalin, noradrenalin and cortisol levels are frequently observed in acute and chronic noise experiments.

According to the general stress model, neuroendocrine arousal suppresses the immune system, influences the metabolic state of the organism, and acts as a mediator along the pathway from the perceived sound to the stress-related disease. Some established risk factors may be affected. For example, risk factors for ischemic heart disease, including blood lipids, glucose level, haemodynamic and haemostatic factors, can be elevated by neuroendocrine arousal (Babisch, 2002).

1.4.2 Theory of the four primary interferences

In this theory, Miedema (2007) proposes four primary interferences caused by environmental noise, which may be accompanied by acute stress responses. These primary effects can lead to long-term effects, and chronic stress is proposed to play an important role.

Sound masking route (communication disturbance)

Sound masking reduces speech comprehension, which may limit speech and human interaction in noisier environments.

Attention route (concentration disturbance)

Attention involves selection of elements such as visual impressions, acoustical impressions or mental representations and selecting, ending or redirecting attention to each. Attention can be focused, or it may be divided over more elements. Noise can negatively affect processes requiring attention.

Arousal route (sleep disturbance)

Higher levels of arousal lower the probability of falling asleep or continuing sleep. Because of its arousal potential, sound can prevent a person falling asleep, affect sleep quality and cause awakening.

Affective—emotional route (fear and anger)

Many sounds are neutral. However, some types of noise can cause affective—emotional responses. Examples include fear and anger.

1.4.3 Effect modifiers

Other factors considered include social and psychological effect modifiers. There is a growing body of literature on the psychological and psychosocial modifiers of annoyance and dissatisfaction due to noise (Guski, 1999; Hatfield et al., 2001; Kroesen et al., 2010; Nitschke et al., 2014; Schreckenberg et al., 2010).

Annoyance

Annoyance is defined as 'a feeling of displeasure associated with any agent or condition, known or believed by any individual or group to adversely affect them' (Berglund et al. 1999). Noise annoyance is a feeling of resentment, displeasure, discomfort, dissatisfaction or offence caused by noise interference. It is a well-established construct in the study of environmental noise and is considered an important end point for measuring the impact of noise in exposed populations.

However, its relationship with health remains uncertain. In Australia annoyance is often considered an issue of amenity. But it forms an important part of the regulatory framework for noise.

It is not yet possible to predict noise annoyance on an individual level, given the many exogenous and endogenous factors that affect it. However, relationships between noise exposure and annoyance can be understood together with several effect-modifying factors. To assess noise-induced annoyance at the population level, a standardised questionnaire can be used. The percentage of respondents who report being highly annoyed can then be used as a prevalence indicator for annoyance in the population (WHO, 2011).

Several theoretical models, including those described above (Babisch, 2002; Miedema, 2007) consider annoyance on a causal pathway to health effects such as stress, cardiovascular effects and sleep disturbance.

1.5 Effects of environmental noise on health and related outcomes

Early research on the health effects of noise is from research into occupational health, and subsequently environmental health, in the 1960s and 1970s in Scandinavia, Europe and the US, as well as Australia. Environmental noise has become an increasingly important issue and many more studies on the health effects of noise have been done over the past few decades. The focus of these studies has shifted from the effect of noise on hearing and cardiovascular health to its broader effect on wellbeing, quality of life and amenity.

While environmental noise is generally recognised as a problem, the extent to which noise adversely affects health, particularly where subjective measures are used, is the subject of continued discussion. This section provides a brief overview of the effects of noise on health.

1.5.1 Effects on hearing

A person who is not able to hear as well as someone with normal hearing (hearing thresholds of greater than 25 dB in both ears) is said to have hearing loss. Around 2.1 million Australians are affected by complete or partial hearing loss (ABS, 2012).

Prevalence of hearing loss is age related: less than 1 per cent of people under the age of 15 are affected by hearing loss, while three in every four people over the age of 70 are affected. In about one-third of people with hearing loss, exposure to excessive noise was reported to be at least partially responsible.

The most common sources of noise injury are workplace noise and recreational noise (Wilson, 1998). Further consideration of exposure to occupational or recreational noise-induced hearing loss is outside the scope of this document.

1.5.2 Effects on health and human response other than hearing loss

Sleep

Sleep is essential for human function. A good night's sleep is also considered essential for quality of life. Sleep disturbance is a common complaint of noise-exposed populations and has the potential to affect health and quality of life.

Sleep parameters can be measured in terms of immediate effects, after-effects and long-term effects. Immediate effects include arousal, sleep stage changes, awakenings, body movements, total wake time and autonomic responses. After-effects include sleepiness, daytime performance and cognitive deterioration. Long-term effects include self-reported chronic sleep disturbance. Chapter 3 addresses noise and sleep disturbance.

Cardiovascular disease

Cardiovascular disease includes ischaemic heart disease, myocardial infarction, hypertension (high blood pressure) and stroke. The number of epidemiological studies on the association between exposure to road traffic and aircraft noise and hypertension and ischaemic heart disease has increased in recent years. Very few studies have investigated the cardiovascular effects of exposure to rail noise (WHO, 2011). Chapter 4 addresses noise and cardiovascular disease.

Cognitive performance

Most observational studies examining cognitive performance are done in children, with experimental studies often involving young adults. Few studies investigate the effects of environmental noise on older adults.

Outcomes investigated include attention, memory, reading comprehension and mathematical tasks.

Chapter 5 addresses noise and cognition.

1.5.3 Other reported health effects and outcomes

Mental health

Environmental noise is not believed to be a direct cause of mental illness, but it is thought to accelerate and intensify the development of latent mental disorders (Berglund et al., 1999).

The effect of noise is complicated. Research suggests that poor psychological health is associated with greater annoyance responses. Studies in adults have found that noise exposure relates to an increase in reported psychological symptoms such as anxiety and depression, rather than to clinically diagnosable psychiatric disorders.

Overall, evidence suggests that in adults and children, noise exposure is unlikely to be associated with serious psychological illness. However, there may be effects on wellbeing and quality of life (Clark and Stansfield, 2007).

Birth outcomes

Ristovska et al. (2014) conducted a systematic review looking at the association between exposure to noise and birth outcomes. The evidence suggests an adverse effect on birth weight. Only a small number of studies have looked at other reproductive outcomes, and no clear links have yet been established.

Vulnerable groups

Particular sub-groups of the population are more vulnerable to experiencing annoyance or adverse health effects from noise.

Vulnerable groups include people with particular diseases or medical problems; people in hospital or rehabilitating at home; people dealing with complex cognitive tasks; those who have a visual or hearing impairment; babies and children; and the elderly.

These groups should be considered when recommending noise regulation or protection, including types of noise effects and specific environment and lifestyle factors (Berglund et al., 1999).

2 NOISE EXPOSURE AND REGULATORY APPROACHES IN AUSTRALIA

This chapter examines the noise environment in Australia. While most of Europe has been able to build a picture of the types and extent of noise exposure across the continent, a lack of systematic data for the Australian context makes understanding and quantifying our noise environment difficult.

In the absence of information that reliably and systematically maps noise exposure and affected populations, researchers use modelled or measured information from significant sources such as aircraft and road traffic.

Complaints information and social surveys may provide some insight into the impact noise has on communities and individuals. These may or may not be typical of how the general population responds.

Both types of information are useful. Modelled and measured data provides an objective measure of noise levels. Complaints and social surveys provide further insight into people's subjective or physical responses to noise. However, complaints data does not always correspond to areas with the highest recorded noise levels. This underscores the subjective nature of noise and suggests other factors such as habituation are important.

The availability of different types of noise data varies, and information is available for some jurisdictions but not others. For example, Airservices Australia provides online summaries of noise monitoring data from major airports that are updated quarterly. Information on road and rail traffic may be available for major developments but obtaining this data is logistically difficult. This information and other data are needed if we are to build a picture of noise exposure across Australia (Airservices Australia, 2015a, b).

This chapter describes some of the common environmental noise sources and provides examples of the types of data available. It summarises the regulatory response to major sources and examines noise mapping in the European context under *European Noise Directive (END) 2002/49/EC relating to the assessment and management of environmental noise* (European Union, 2002).

A significant portion of this chapter focuses on road, aircraft and rail noise, which are characterised by lower, intermittent and higher frequencies respectively. Most research is done on road, aircraft and rail noise because their characteristics are similar to other noises.

2.1 Sources of noise exposure

2.1.1 Road traffic noise

Road traffic noise is mainly generated from the engine and from frictional contact between the wheels, the ground and the air. Road contact noise exceeds engine noise at speeds higher than 35km/hour. However, the physical principle responsible for generating noise from contact between the tyre and the road is less well understood (Berglund et al., 1999). It is estimated that more than 70 per cent of environmental noise (unwanted sound) in urban Australia is due to road traffic (Marquez et al., 2005).

Noise levels from traffic can be predicted from the traffic flow rate, the speed of the vehicle, the proportion of heavy vehicles, and the nature of the road surface. Vehicle noise is related to traffic speed. As speed-changing traffic is noisier than steady traffic, congestion may add to noise.

Congestion typically reduces traffic noise due to lower vehicle speeds. An indirect consequence of congestion is an increase in night-time freight as freight operators, encouraged by government agencies, try to avoid daytime congestion. Noise from heavy truck exhaust and gear changes as well as engine noise and braking, is a particular problem. Rising traffic levels and growing freight movements lead to increasing violations of transport noise level guidelines (Marquez et al., 2005).

In highly urbanised Australia, the population exposed to noise is mostly concentrated in metropolitan areas (Brown and Bullen, 2003). Most noise impacts of traffic occur when people are in their homes. Estimating community exposure requires estimating the levels of road traffic noise at the facades of dwellings in Australian cities.

A survey of road traffic noise in five capital cities by Brown and Bullen (2003) shows the proportion of dwellings affected by road traffic noise. The study was done in 1997–98. At the time, it provided the best available estimate of road traffic noise exposure in urban Australia. The study drew a random sample of dwellings from the urban centres in each capital and estimated road traffic noise exposure at each dwelling.

The results show that 8 to 20 per cent of dwellings are exposed to $L_{A10,18h}$ levels above 63 dB and 5 to 11 per cent above $L_{A10,18h}$ 68 dB. L_{A10} is the noise level exceeded for 10 per cent of the measurement period. $L_{A10,18h}$ is the average of L_{A10} noise levels from 6am to midnight.

Sydney was significantly different to the other cities with a higher proportion of dwellings subject to external noise between $L_{A10,18h}$, 60 and 70 dB. The study suggested this might be due to a different pattern of road use and Sydney's physical location.

Figure 2-1 shows an estimate of the proportion of dwellings in the urban centres of Sydney, Melbourne, Brisbane, Perth and Adelaide where calculated traffic noise exceeds values on the $L_{A10,18h}$ scale.

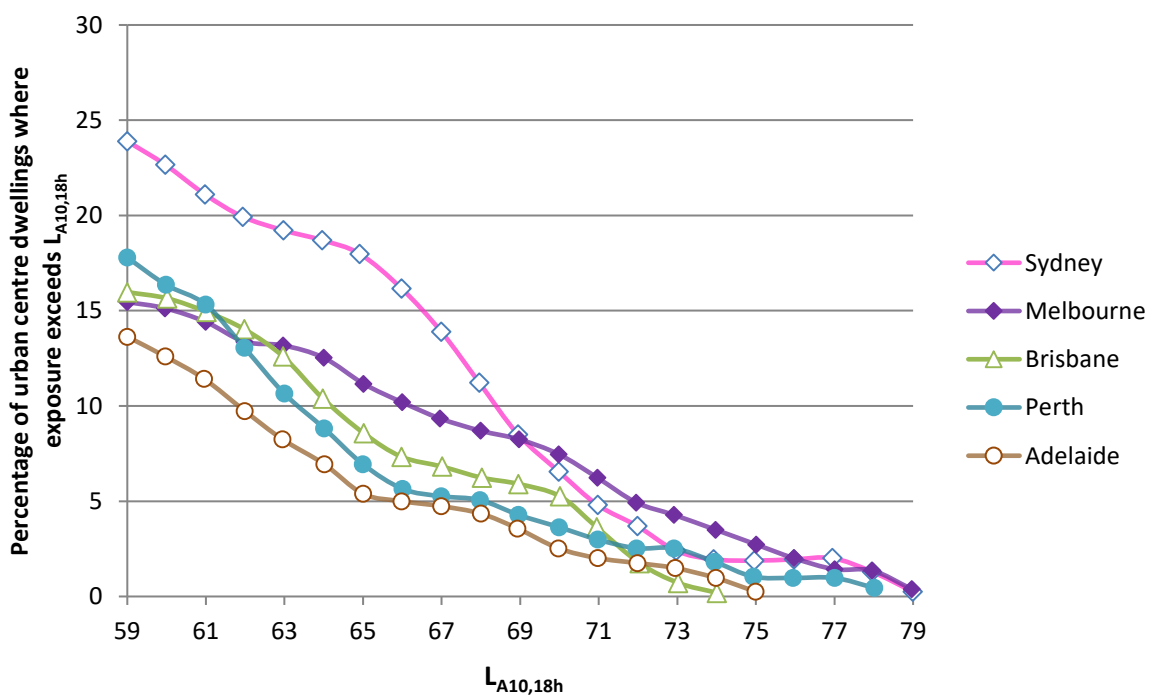


Figure 2-1: Cumulative noise exposure of dwellings in Australian capital cities, $L_{A10,18h}$
(Adapted from Brown and Bullen 2003)

Since that survey, vehicle fleet mix has changed. The ABS Motor Vehicle Census (2014) shows a slight decrease in the proportion of passenger vehicles in Australia with these accounting for about 75.4 per cent of all registered vehicles in 2014 as opposed to about 80 per cent in 1999. This has been offset by a rise in the proportion of light commercial vehicles, heavy rigid trucks, buses and motorcycles in each jurisdiction. The total number of vehicles increased from about 12.3 million in 1999 to about 17.6 million in 2014. The passenger vehicle fleet rose from about 9.7 million to about 13.3 million in the same period.

These changes will have an impact on the noise environment and the characteristics of the noise experienced. A noise measurement survey by Victoria's Environment Protection Authority (EPA) compared noise measurements in 2007 with data collected in 1978 (EPA Victoria, 2007). It measured noise levels at 50 sites across the inner, middle and outer suburbs of Melbourne and showed that despite the growth in traffic volumes, noise levels across Melbourne were similar to those in 1978 (Figure 2-2). This graph depicts noise levels in terms of the $L_{Aeq,1hr}$.

These results suggest that while traffic volumes have grown and the mix has changed, quieter vehicles and other factors may be offsetting any rise in noise. Examples include improvements in road surface and better policies for new and upgraded roads. However, increasing residential densities along major urban roads means a greater percentage of the population is likely to be exposed to higher traffic noise.

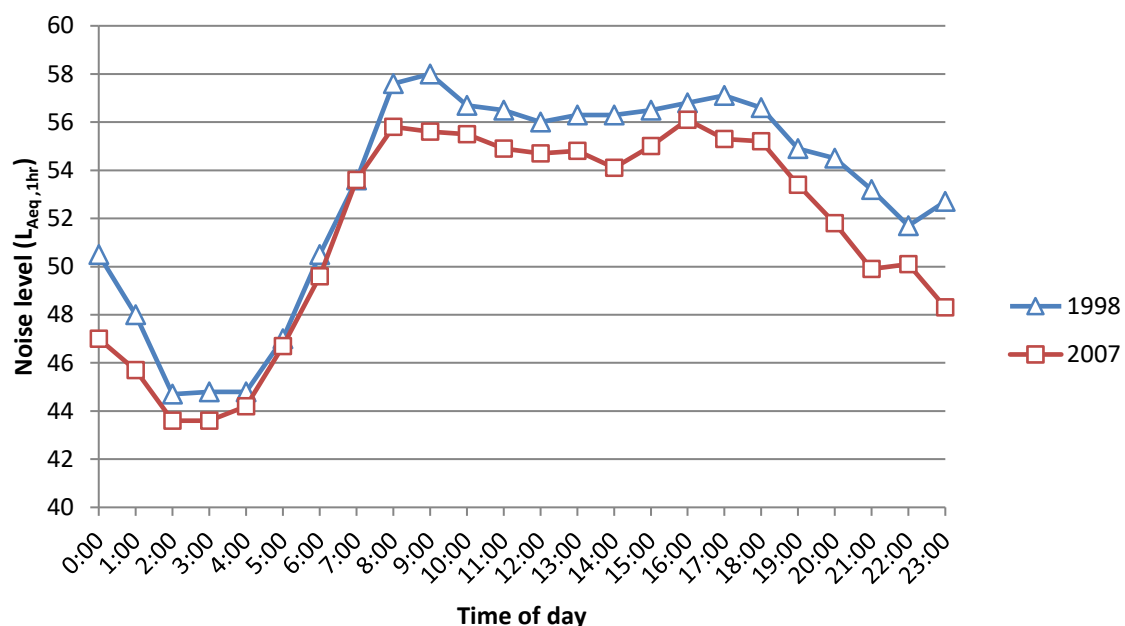


Figure 2-2: Average noise levels for each hour on weekdays for 1978 and 2007 in Melbourne (Adapted from EPA Victoria, 2007)

Following EPA Victoria's noise measurements in 2007, WSP Acoustics did environmental noise modelling for the authority on the greater Melbourne area in 2013. It provided estimates of the population exposed to a range of noise levels. Using Sound PLAN, it constructed a three dimensional representation of the environment of greater Melbourne. This provided noise maps to visualise noise exposure. These maps can inform EPA Victoria's input into activities such as land use planning, transport planning and design standards that change the community's exposure to noise. Modelling for each scenario considered ground contours, road and traffic data, locations of sensitive receptors, noise barriers and other inputs affecting the road traffic noise environment (WSP, 2014).

Mitigation of road traffic noise

Noise mitigation of road traffic tends to focus on controlling noise at the source, between the source and the receiver (noise pathway), and at the receiver location. Effective noise management may use a combination of mitigation techniques to reduce noise. Effectiveness is the degree of reduction achieved and perceptions of change in the noise environment. It also includes practical considerations such as feasibility of construction and if these measures are reasonable.

Noise mitigation techniques include vehicle noise control (Department of Infrastructure and Regional Development, Australian Design Rules) and controlling traffic (reducing volumes, controlling speed or decreasing flow).

Construction techniques include road alignments (vertical and horizontal), low noise road surfaces and noise barriers (NSW Environment Protection Authority Road Noise Policy, 2011).

Urban planning controls and acoustic insulation for new buildings next to busy roads are also used to reduce noise (Australian Building Codes Board and some state planning departments).

The results of these different options vary.

Controlling vehicle noise and traffic can reduce noise by 1 to 5 dB(A).

Noise barriers can cut up to a 10 dB(A) although effectiveness depends on barrier height, length, material density and distance from noise source. However, barriers can only be fitted along no-access roadways and many urban roadways have road frontages from properties. Extra height in barriers can reduce noise further, although these are restricted by structural elements and aesthetics. Retrofitting noise walls to existing roads is expensive (Austroads, 2005).

2.1.2 Aircraft noise

Aircraft operations generate substantial noise, exposure to which is concentrated around airports. Take-off produces intense noise, including vibration and rattle, while landings generate noise in long low-altitude flight corridors. For the most part, larger and heavier aircraft are responsible for more noise than lighter aircraft (Berglund et al., 1999).

In older, turbojet-powered aircraft, the main mechanism of noise generation was turbulence created by the jet exhaust mixing with surrounding air. In more modern aircraft this noise source is significantly reduced by using high by-pass ratio turbo-fan engines that surround the high velocity jet exhaust with lower velocity airflow generated by the fan. Noise can also be generated by the fan itself, particularly during landing and taxiing. Multi-bladed turbo prop engines can produce relatively high levels of tonal noise (Berglund et al., 1999).

The overall sound pressure levels from airports can be determined from the number and types of aircraft, their flight paths, the proportions of take-offs and landings, and the atmospheric conditions. Airports hosting helicopters or smaller aircraft used for private business, flight training and leisure purposes may also contribute to significant noise associated with flight paths.

Over the past three decades, Australia has seen a substantial increase in aircraft numbers and movements. Kingsford Smith airport in Sydney has experienced the greatest growth in flight movements (BITRE, 2014). This increase, seen in Figure 2-3, has resulted in continued exposure to aircraft noise, particularly on communities close to airports and underneath flight paths. This is despite reduced noise emissions from newer types of aircraft.

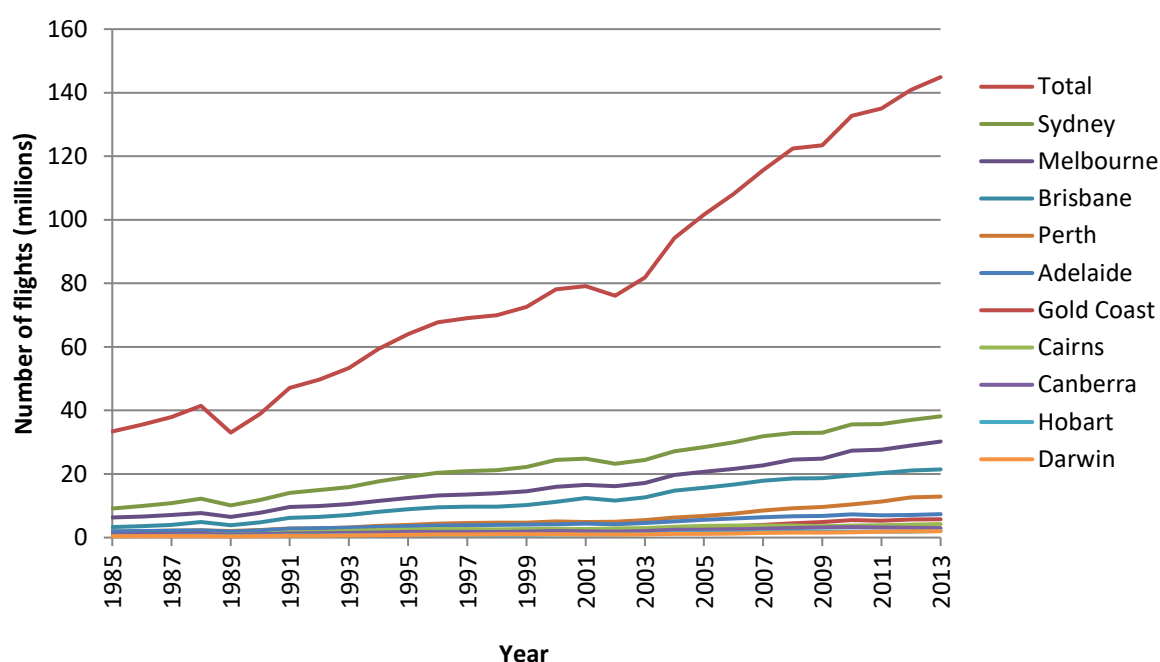


Figure 2-3: Aircraft movements at Australian airports 1985-2013 (Data sourced from Bureau of Infrastructure, Transport and Regional Economics (BITRE) 2014a)

Australian Noise Exposure Forecast

Information about aircraft noise in Australia is provided through the Australian Noise Exposure Forecast (ANEF). This forecast system is based on findings from a major socio-acoustic survey done near several Australian airports (Hede et al., 1982).

The study shows that a weighting period from 7pm to 7am gives the best correlation between noise dose and community reaction. The contours relate to the total noise energy received by locations on the ground near an airport on an annual average day. They show predicted future aircraft noise levels.

While ANEF is an effective land use planning tool, it does not convey information about the actual aircraft noise levels experienced at a given location. This means other noise descriptors are often used as supplements to ANEF contours.

ANEF is the officially endorsed chart for an aerodrome.

N contours

N contours are designed to supplement ANEF and better describe aircraft noise levels to the public. They were developed by the Commonwealth Department of Infrastructure and Transport in consultation with industry and the community. N contours measure the number of noise events per day exceeding 60, 65 or 70 dB (see Table 2-1) and show the expected noise levels in a particular area (Department of Transport and Regional Services, 2000).

Table 2-1: Description of N contours

N contour	Definition
N60	Number of events exceeding 60 decibels per day
N65	Number of events exceeding 65 decibels per day
N70	Number of events exceeding 70 decibels per day
Night contours	For example: 6 or more events exceeding 60 decibels per day

Australian Noise Exposure Index

The Australian Noise Exposure Index (ANEI) is similar to ANEF but based on historical data, where flight paths and aircraft movements are known rather than forecast. It uses an integrated noise model comprising data for the flight path, aircraft type, runway used and time of day (weighted for 7pm to 7am).

ANEI contours are plotted on a map using geographic information systems (GIS) software. The contours are consistent with flight tracks and aircraft operations for the period.

Figure 2-4 shows ANEI contours for Sydney airport. The population beneath the ANEI contours is estimated using the latest census data and suburb boundary information.

The Australian Noise Exposure Concept (ANEC) is an illustration of aircraft noise exposure at a site, using data that may bear no relationship to actual or future situations.

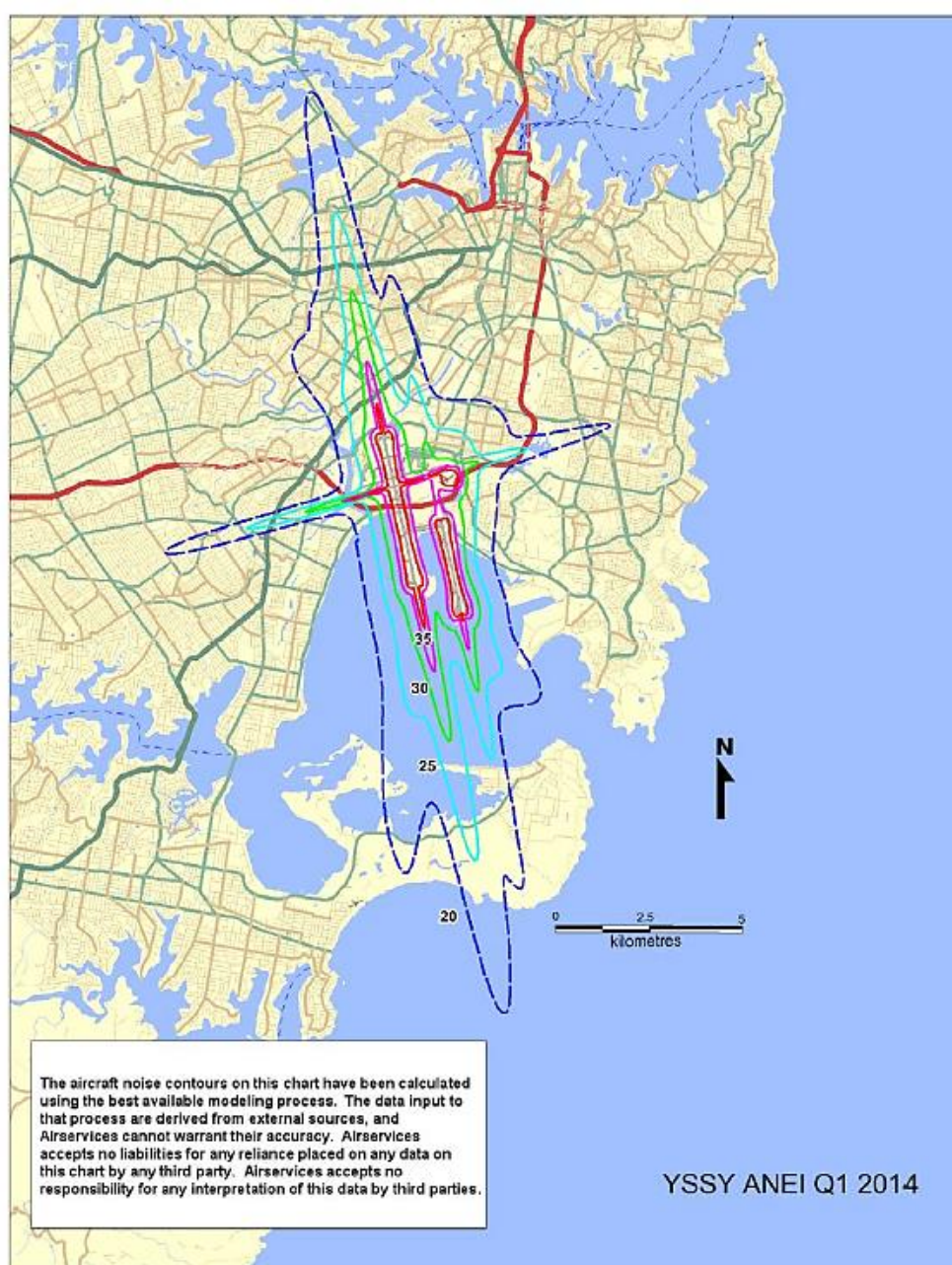


Figure 2-4: ANEI contours for Sydney Airport, January to March 2014 (Airservices Australia 2015)

Aircraft noise monitoring

Noise monitoring is done at major airports including Adelaide, Brisbane, Cairns, Canberra, Gold Coast, Melbourne, Perth and Sydney. Information includes the identity, flight path and altitude of each aircraft operating to and from the airport, and the noise levels produced by individual aircraft. The information is collected for each 24-hour period per week by fixed noise monitors or environmental monitoring units along the flight path.

This data can be used in several ways to show average noise during a period, background noise levels or the number of noise events over a certain threshold.

Airservices Australia provides online summaries of noise monitoring data from major airports that are updated quarterly (Airservices Australia, 2018a). It also displays historical and near real-time noise data from each monitoring unit in WebTrak (Airservices Australia, 2018b).

Mitigation of aircraft noise

Aircraft operating in Australia are required to adhere to noise standards set out by the International Civil Aviation Organisation in *Annex 16 — Environmental Protection, Volume I — Aircraft Noise* to the Convention on International Civil Aviation (ICAO, 2008).

Some airlines seek to reduce noise by buying quieter aircraft or organising their fleet so quieter aircraft fly at sensitive times. Airlines can also take a continuous descent approach, using technology to glide into the airport in one smooth descent.

Airports and airlines work together to minimise noise exposure during night hours. This includes procedures such as preferred runways and flight paths and reducing engine thrust when safe to do so (Airservices Australia and Australian Airports Association).

Curfews attempt to balance airport commercial operations and safety requirements with the need to reduce night-time aircraft noise. They do not stop all aircraft movements, but they limit take-offs and landings by restricting the type of aircraft that can operate, the runways they can use and the number of flights. Curfews usually operate from 11pm to 6am, with most commercial aircraft prohibited from flying during that time. The exceptions to this are shoulder movements, which occur from 5am to 6am and 11pm to midnight. These are permitted on a quota basis to account for differences during the northern hemisphere's summer, which affects flying schedules (Airservices Australia and Australian Airports Association). Curfews are in place at Sydney, Adelaide, Coolangatta and Essendon airports (Department of Infrastructure and Regional Development, 2016).

2.1.3 Rail noise

Rail noise depends on many factors, including the speed at which the train is travelling. Noise characteristics vary depending on the type of engine, wagons, the rails and their foundations, as well as the roughness of the wheels and the rail. Small radius curves in the track can lead to very high frequency sound, often called 'wheel squeal'. Noise is also generated by running engines, whistles and loudspeakers, and shunting operations in marshalling yards.

High-speed trains have been associated with sudden, but not impulsive, rises in noise. At speeds greater than 250 km/hour, the proportion of high frequency sound energy increases with the sound similar to an overflying jet aircraft (Berglund et al., 1999).

The Cooperative Research Centre (CRC) for Rail Innovation (CRC for Rail Innovation, 2011) classifies rail noise as:

1. Rolling noise: the vertical excitation of the rail and wheel generated by variations or roughness of the wheel or the rail surfaces
2. Impact noise: the result of discontinuities in the running surfaces of the rail and wheel
3. Traction noise: generated by power units of any kind including diesel or electrical power sources. It covers possible mechanisms associated with the function of converting the supply energy to mechanical work
4. Friction braking noise: generated by the interaction between the friction material and the rotating element. In some cases this is seen as a subset of traction noise
5. Curving noise: caused by friction induced self-excitation of the wheel and rail in the lateral direction on low radius curves, including flanging noise and curve squeal noise

6. Aerodynamic noise: caused by disturbance of air flow over the train, becoming significant at high speeds (greater than 200km/hour)
7. Other noise sources: including wagon 'bunching', coupler noise, warning signals, communication systems noise, stabling and yard noise, maintenance noise, and internal noise such as air conditioning and gangway noise.

Growth in rail sector

The use of rail freight (rolling stock or fleet) is expected to grow 1.9 times the 2010 level by 2030 (BITRE, 2014b) .

Rail is competitive for long distance non-bulk freight, such as from Sydney to Perth. This expanded use of rail for freight may increase noise in metropolitan areas and in rural areas that have not been previously affected.

Figure 2-5 shows the increase in sending freight by road and rail to 2013, with rail freight set to increase significantly (BITRE, 2014c).

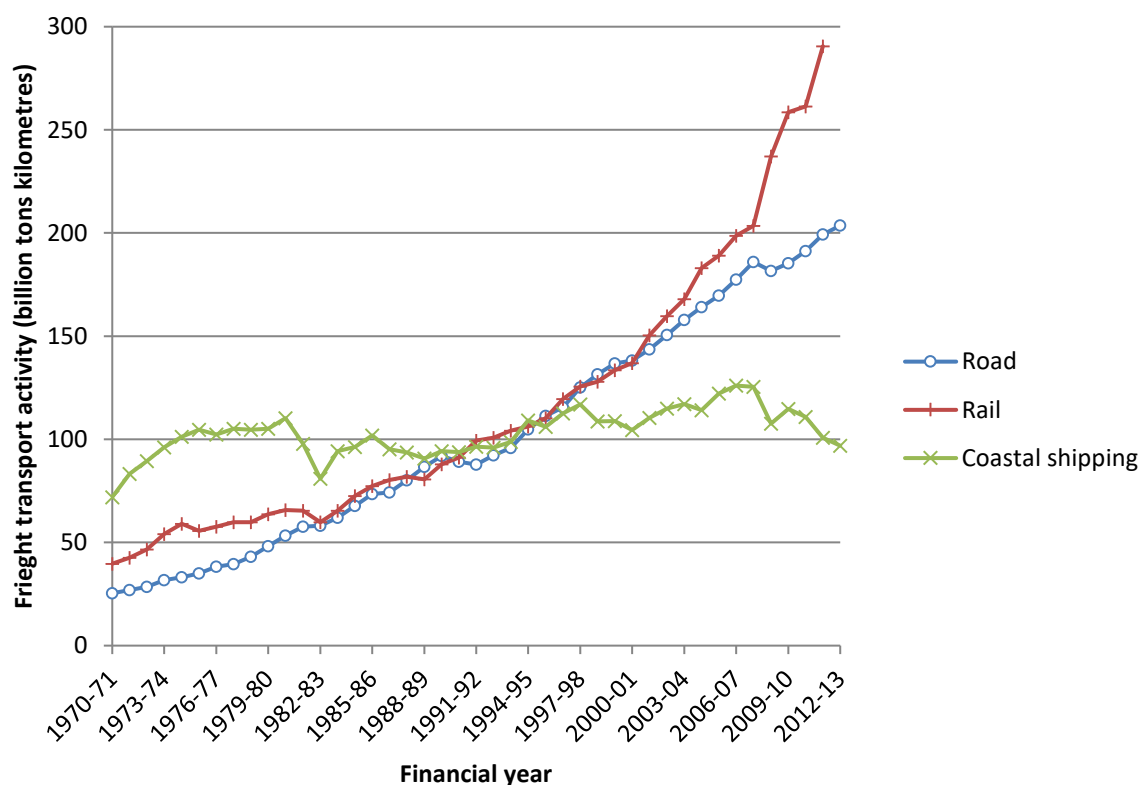


Figure 2-5: Domestic freight transport activity by mode (Adapted from BITRE 2014c)

Growth of passenger rail

Rail passenger transport is not expected to increase as much as freight, due to the dominance of private cars. Very high speed trains have been proposed to connect Brisbane, Sydney and Melbourne, with the first link between Sydney and Canberra operational by 2035 (Department of Infrastructure and Regional Development, 2013). If high-speed rail is a genuine possibility in Australia, its health impact should be considered now.

Proportion of the population exposed to rail noise

Estimates from Europe indicate the noise contribution from railways is around 10 per cent of the total noise burden from both roads and railways (EPA, 2014). There are no estimates for Australia, but an example of rail noise exposure is shown below.

In 2002 the former NSW Rail Infrastructure Corporation undertook modelling work on five priority lines in the Sydney metropolitan rail network. The percentage of receivers (people) exposed to different noise levels are shown for two of these train lines in Figure 2-6. With increasing urban density and the development of new passenger and freight lines, the number of people exposed will have steadily increased.

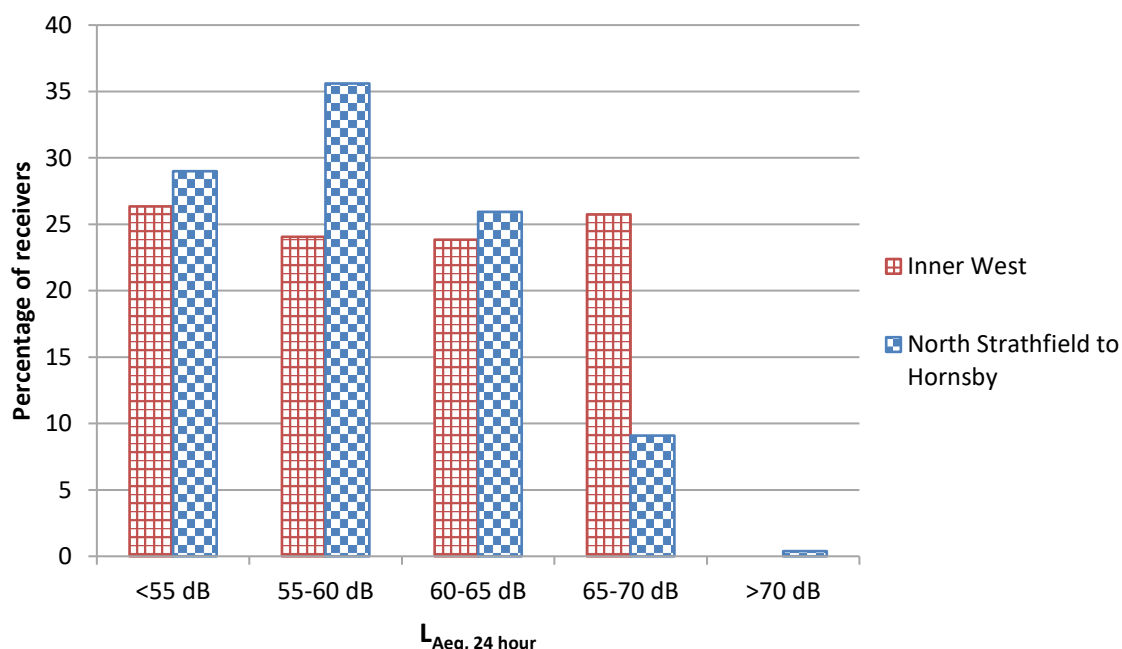


Figure 2-6: Percentage of receivers exposed to various noise categories along two major railway lines in Sydney

Mitigation of rail noise

Several European studies confirm that measures to reduce noise at the source are more cost effective than constructing noise barriers. Mitigation strategies tend to follow those outlined for road traffic noise. This may be problematic for rail upgrades, as source control measures usually provide only a small decrease in noise levels and may take significant time to be installed.

Examples of types of mitigation include: minimisation of wheel and rail roughness (for example regular wheel and rail grinding); reduction of wheel and rail acoustical radiation; track lubrication to reduce squeal on curves; and lessening of sound propagation using rail screens, barriers and vehicle skirts.

Appropriate combinations of measures applied to wheel and track design can reduce noise by more than 10 dB(A) L_{Aeq} . However, this requires a coordinated approach between rolling stock operators and infrastructure owners. This can prove challenging in many contexts, particularly where responsibility for vehicles and track are segregated (CRC for Rail Innovation, 2011).

2.1.4 Industrial noise and other fixed noise sources

Noise from mechanised industry creates problems both for indoor and outdoor settings. The noise is generally due to machinery and often increases with the power of the machines. The noise generated by machinery may contain mainly low or high frequencies, tonal components, be impulsive or have unpleasant and disruptive temporal sound patterns. Rotating and reciprocating machines produce sound that includes tonal components.

Air-moving equipment tends to create noise with a wide frequency range. Components or gas flows that move at high speed result in high sound pressure levels (Berglund et al., 1999). Examples include fans and steam pressure relief valves, as well as operations involving mechanical impacts, such as stamping, riveting and road breaking.

Fixed sources of industrial and other noise include: extractive industries – oil, gas and mining, manufacturing, construction, agriculture, military and power generation.

The National Health and Medical Research Council (NHMRC) has investigated the evidence on wind farms and human health and concluded there is no consistent evidence that wind farms cause adverse health effects in humans. Given the poor quality of current direct evidence and the concern expressed by some community members, high quality research into possible health effects of wind farms, particularly within 1500 metres, is warranted (NHMRC, 2015).

2.2 Social surveys of noise annoyance

South Australia noise perception and quality of life survey (2014)

In South Australia, a representative state-based survey interviewed 3015 people using a standardised noise annoyance survey tool (Nitschke et al., 2014). Noise from road transport was reported as a source of annoyance (little to extreme) by the highest proportion of respondents (27.7 per cent), followed by noise from neighbours (22 per cent), construction noise (10.0 per cent), air conditioner noise (5.8 per cent), rail transport noise (4.7 per cent) and industrial noise (3.9 per cent).

The survey indicated that 25.1 per cent of people surveyed lived less than 50 metres from a major road in South Australia. When the results were extrapolated to the state population, 6.9 per cent of people were estimated as being highly annoyed by noise from at least one source.

Perth community noise survey (2011)

The West Australian Department of Environment and Conservation (DEC) undertook a survey in 2011 to evaluate community attitudes to and experience of local noise. A stratified random sample of 410 respondents from the greater Perth area was surveyed. Of the respondents, 30.2 per cent considered noise a problem in their area, with 12.7 per cent considering noise a significant problem, and 5.6 per cent considering it to be a major problem (DEC, 2011).

Victoria noise survey (2007)

A social survey of 1213 respondents by Environment Protection Authority Victoria was done in 2006 to understand the impact of noise on the community. It found that almost half of all Victorians (49 per cent) had been disturbed or annoyed by environmental noise at some stage in the preceding 12 months (EPA Victoria, 2007).

2.3 Relevance of urban and built form, climate and behaviour to noise exposure

The urban population of Australia accounts for about 70 per cent of the total population (ABS, 2014). Concerns about the growth of larger cities have placed more focus on urban design and planning in the past five years, with most state governments producing strategic plans for their capital cities. These include policies to minimise outer suburban sprawl and encourage higher density residential development around major activity centres and routes served by public transport. Policies to abate the problem of increases in external noise have also been put forward by public and private sector agencies.

The main responses to reduce noise are through building design, public engineering works and land use planning. Examples of good architectural design of buildings to reduce noise include orientation of buildings and habitable rooms away from the noise source. Examples of public engineering works include barriers and landscaping close to roads and railways as well as quieter roads and railways. Examples of land use planning approaches include separating noisy transport routes from noise sensitive areas, managing traffic and reducing speed, and restricting the slope of roads and curves in railway tracks to decrease noise.

In NSW the State Environment Planning Policy (Infrastructure) 2007 sets out specific planning provisions and controls for developments in rail corridors and near busy roads.

Legislated planning mechanisms are important at the earliest stage of the development, such as at the zoning, subdivision or initial development design stages. This helps manage the potential for land use conflict around noise before construction starts.

For residential dwellings near noise sources, the effectiveness of exposed façades in attenuating noise is another important factor. The simplest types of facades reduce sound by about 15 dB(A) from outside to inside when the windows are closed. Double brick walls generally provide adequate noise reduction. Weatherboard walls can be upgraded with in-cavity insulation, although the effectiveness is relatively small. Insulation of roofs is also important, particularly in areas where aircraft noise is an issue.

Due to their lightweight construction, windows are generally the weakest point in the sound propagation path. Single and double window glazing can reduce noise by up to 30 and 35 dB(A) when closed. However, when windows are slightly open, outside sound levels are reduced only by 10 to 15 dB(A). This is particularly important as many Australians prefer their windows slightly open at night for ventilation. In Western Australia state planning policies recommend fans or air conditioning in conjunction with upgraded glazing to ensure adequate ventilation when windows are closed to exclude noise.

2.4 Regulatory approaches and mechanisms to limit exposure

2.4.1 Road traffic noise

The Australian Design Rules for motor vehicles are national standards for safety, anti-theft and emissions. They are generally performance based and cover issues such as occupant protection, structures, lighting, noise, engine exhaust emissions, braking and other items. Under the *Motor Vehicle Standards Act 1989*, four rules apply to noise from vehicles. These define the limits on external noise generated from cars, trucks, buses, motor cycles and mopeds (Department of Infrastructure and Regional Development, Australian Design Rules). Similarly, state-based road rules prohibit driving in a way that makes unnecessary noise. An example includes Victorian Road Safety Rule 291 that states: “a person must not start a vehicle, or drive a vehicle, in a way that makes unnecessary noise or smoke”.

Noise from engine brakes is the greatest source of community complaint against the heavy vehicle industry. In November 2007, Australian transport ministers unanimously approved a regulatory proposal and model law for an in-service engine brake noise standard and testing procedure for heavy vehicles. The standard would provide an objective enforcement approach that defines a limit on the noise emitted from an engine brake. However, this has not yet been implemented across the states and territories due to technical and operational issues (National Transport Commission, 2013). State-based vehicle standards put limits on noise from in-service noise but these are often less stringent than Australian Design Rules.

Traffic restrictions and traffic calming measures have generally reduced traffic noise due to changes in: traffic volume and composition, road layout and surface, vehicle speed and driving style. The use of traffic calming and restrictions may need more attention to address urban noise in residential areas. Transportation and town planners may need to explore freight traffic patterns, particularly in areas with increasing urban density, and consider approaches such as special routing, freight traffic centres and ways to encourage more environmentally friendly freight traffic.

Efforts to reduce noise exposures through home insulation and construction of noise barriers in communities exposed to road traffic noise have also been made. Australian Standard 3671:1989, Acoustics – Road traffic noise intrusion – Building siting and construction, provides guidance on acoustic requirements for residential dwellings near roads. There are also statutory approval processes for new and redeveloped roads.

Examples of policies used in these approval processes in NSW include the Road Noise Policy (NSW EPA, 2011), which assigns acoustic design requirements. The NSW State Environment Planning Policy (Infrastructure) requires homes built alongside busy road and rail corridors to incorporate measures to achieve required internal noise levels. NSW Roads and Maritime Services has a specialised noise abatement program to address road traffic noise through a range of approaches.

2.4.2 Aircraft noise

Air Navigation (Aircraft Noise) Regulations (1984) require all aircraft operating in Australian airspace to comply with noise standards and recommended practices under the Chicago Convention (Convention on International Civil Aviation). These are set out in the International Civil Aviation Organisation (ICAO) document Annex 16, Environmental Protection – Volume I (ICAO, 2008). Aircraft found to be compliant are issued with a noise certificate. Aircraft without a noise certificate are not permitted to operate in Australia.

Flight activities and aircraft curfews are the responsibility of Airservices Australia, individual airport authorities and the Commonwealth government. The *Airports Act (1996)* was passed to cover environmental protection regulations. It governs noise and other environmental issues, but only 21 airports are covered by this act.

The Australia Standard AS 2021:2015 Acoustics – Aircraft noise intrusion – Building siting and construction (Standards Australia, 2015) provides guidance on the siting and construction of buildings near airports to minimise aircraft noise. The assessment of potential aircraft noise exposure at a given site is based on the Australian Noise Exposure Forecast (ANEF) system. The standard also provides guidelines for the type of building construction necessary to reduce noise to a given level. It is widely referred to in guiding strategic land use planning near airports. The AS 2021:2015 specifies that it is acceptable to build noise-sensitive developments in areas where ANEF is less than 20. Noise-sensitive developments are conditionally acceptable between ANEF 20 and 25 provided required internal sound levels are achieved through building design. However, some airport noise complaints come from areas beyond ANEF 20 contours.

Noise insulation programs were established around Sydney Airport in 1995 and Adelaide Airport in 2000. Residential properties with greater than ANEF 30 contour exposure and public buildings (schools, churches, day care centres and hospitals) with greater than ANEF 25 contour exposure were eligible for assistance in obtaining insulation. The programs aimed to achieve a 35 dB(A) lowering of noise levels for bedrooms, and 30 dB(A) for living rooms (Department of Infrastructure and Regional Development, 2014). Sydney airport also has a long-term operating plan to manage aircraft noise by directing flights over water and non-residential land and by spreading the noise across different communities (Airservices Australia, 2015a,b).

2.4.3 Rail noise

There has been a great deal of discussion at the national government level about rail infrastructure and ways to improve rail operations. Funds for improving track and rolling stock might be invested in equipment with reduced noise generation. Limited information is available on national efforts to reduce rail traffic noise in concert with rail improvements. However, a national initiative to develop rolling stock standards is being led by the Rail Industry Safety and Standards Board.

Individual states have developed rail noise initiatives, including standards, guidelines and noise abatement programs. These programs include methods for assessing and prioritising requests for mitigation from people particularly affected. Environmental planning guidelines for residential developments near rail corridors set acceptable internal noise levels and provide advice to developers on how to achieve them.

2.4.4 Industrial noise and other fixed noise sources

Control of industry noise affecting communities is the responsibility of planning and environment authorities in the states and territories. Local ordinances or operation restrictions may be needed if construction activities take place in an area with sensitive uses, such as schools or hospital zones, or outside standard construction hours. Reductions in industrial noise can be achieved by encouraging quieter equipment or by zoning controls to separate acoustically incompatible land uses, such as the contrast between residential and industrial zones. Noise emissions, like other environmental emissions, may also be licensed or regulated under relevant environmental legislation.

2.4.5 Other noise sources

Domestic equipment may have times-of-use restrictions, such as grass cutting machines, leaf blowers, chainsaws, domestic air conditioners, mobile air compressors, pavement breakers, and mobile garbage compactors. This includes the use of power tools on residential properties either under state and territory legislation or local government regulation. The former Standing Council on Environment and Water discussed a national policy on noise labelling for portable equipment but this has yet to come to fruition. Noise labelling is required in some states, for example NSW, under the revised *Protection of the Environment (Noise Control) Regulation 2008*.

Other noise sources of concern include that from fireworks and explosives during celebrations, and from children's toys. Australian Standard AS/NZS 8124.1:2002, Safety of toys, includes noise regulations.

2.4.6 Building requirements to protect against noise

The internal acoustic requirements for dwellings are determined by the National Construction Code (NCC, 2016) as well as local councils. The Australian Building Codes Board administers and maintains the code to encourage national consistency based on minimum safety and health requirements. The code is given legal effect by relevant legislation in each state and territory.

Australian Standard 2107:2016, Acoustics—Recommended design sound levels and reverberation times for building interiors, is the standard most commonly referred to in building acoustics. The standard, while not mandatory, sets out recommendations for design sound levels for building interiors. The Australian Association of Acoustical Consultants has also produced a *Guideline for Apartment and Townhouse Acoustic Rating* (AAAC, 2010), a performance-based guideline for insulation. The guideline contains a star rating corresponding to the intrusion of external noise into bedrooms and habitable rooms as shown in Table 2-2. This has been adopted by many in the industry.

Table 2-2: Guideline for acoustic rating of apartments (Adapted from Australian Association of Acoustical Consultants, 2010)

Apartment rooms	External noise intrusion	2 star	3 star	4 star	5 star	6 star
Bedrooms	Continuous noises	36 dB(A)	35 dB(A)	32 dB(A)	30 dB(A)	27 dB(A)
	Intermittent noises	50 dB(A)	50 dB(A)	45 dB(A)	40 dB(A)	35 dB(A)
Other habitable rooms including open kitchens	Continuous noises	41 dB(A)	40 dB(A)	37 dB(A)	35 dB(A)	32 dB(A)
	Intermittent noises	55 dB(A)	55 dB(A)	50 dB(A)	45 dB(A)	40 dB(A)

2.5 Best practice noise exposure information – noise mapping

Broadly defined, noise mapping is a means of presenting calculated and/or measured noise levels in a representative manner over a particular geographic area. The European experience may provide a basis for an Australian approach. The European Union Environmental Noise Directive (END) (2002) applies to noise to which humans are exposed. It focuses on built-up areas, public parks or other quiet areas in an agglomeration, quiet areas in open country, near schools, hospitals and other noise-sensitive buildings and areas (Article 2.1). The END is one of the main instruments to identify noise pollution levels and to trigger the necessary action at member state and European Union level.

In the context of the END, the European Commission has common noise assessment methods (CNOSSOS–EU) for road, railway, aircraft and industrial noise to improve the reliability and comparability of results across the European Union. This framework allows for coherent and reliable strategic noise mapping and action planning. Assessment of noise exposure is done using strategic noise maps with harmonised noise indicators L_{den} and L_{night} for major roads, railways, airports and agglomerations.

In the first phase (June 2007) strategic noise maps were compiled for EU member states. These covered agglomerations with more than 250,000 inhabitants, major roads with more than 6 million vehicle passages a year, railways with more 60,000 train passages a year and major airports with more than 50,000 movements a year.

The second phase (June 2012) produced strategic noise maps for agglomerations with a population of more than 100,000.

The END also determines levels of exposure to environmental noise using the above indicators. Estimates of the number of people living in dwellings exposed to values of L_{den} and L_{night} at the most exposed building façade are done separately for road, rail, air traffic and industrial noise. Where possible and available, information about people living in dwellings with special insulation against noise or with quiet façades is also reported.

Noise maps are only as accurate as the input data and techniques used to calculate sound levels. They may not always accurately depict sound level variations that occur locally. They can also be expensive to produce.

Despite these limitations, noise maps have significant uses for public health in providing estimates of exposure that can help quantify the burden of environmental noise. The European experience provides a useful insight into how similar work might be done in Australia.

3 NOISE AND SLEEP DISTURBANCE

3.1 Introduction and background

Sleep serves an important restorative purpose in promoting functioning and a sense of wellbeing. Obtaining sufficient duration and quality of sleep is important for overall health and wellbeing. Sleep problems are common in many countries, including Australia (Deloitte Access Economics, 2011).

Poor sleep has been linked to numerous adverse consequences, including health conditions such as cardiovascular disease, depression and obesity (Riemann et al., 2011), as well as accidents and disability due to fatigue (Horne and Reyner, 1999), and lost workplace productivity (Iverson et al., 2010; Rosekind et al., 2010). These translate into considerable social and economic costs, with three sleep disorders alone – obstructive sleep apnoea, primary insomnia and restless leg syndrome – estimated to cost the Australian economy \$36 billion a year (Deloitte Access Economics, 2011). The economic costs of sleep problems more broadly (such as daytime sleepiness or short sleep) are estimated to be considerably higher (Deloitte Access Economics, 2011).

Many genetic, lifestyle, health and environmental factors have the potential to influence the quality and amount of sleep. Poor sleep can reflect lifestyle factors such as screen time, physical activity, alcohol consumption and caffeine consumption. Psychological characteristics such as stress, sensitivity and personality characteristics have also been linked to sleep quality.

Environmental noise has long been identified as a potential cause of poor sleep. Reviews conducted to help inform guidelines show a strong basis for believing that environmental noise during the night is a contributor to poor sleep (WHO, 2009). Many recent studies have suggested that exposure to road, rail and aircraft noise is linked to a range of sleep disturbances, including increased arousals (Tassi et al., 2010), insomnia symptoms (Halonen et al., 2012), and poorer self-reported sleep quality (Kim et al., 2014).

3.2 Systematic review of the literature: environmental noise and sleep disturbance

A systematic review of the literature was done for studies from January 1994 to March 2014 on the relationship between environmental noise and sleep. Appendix A details the review's objectives and methodology.

3.2.1 Search results

The results of the search process are summarised in the following PRISMA flow chart.

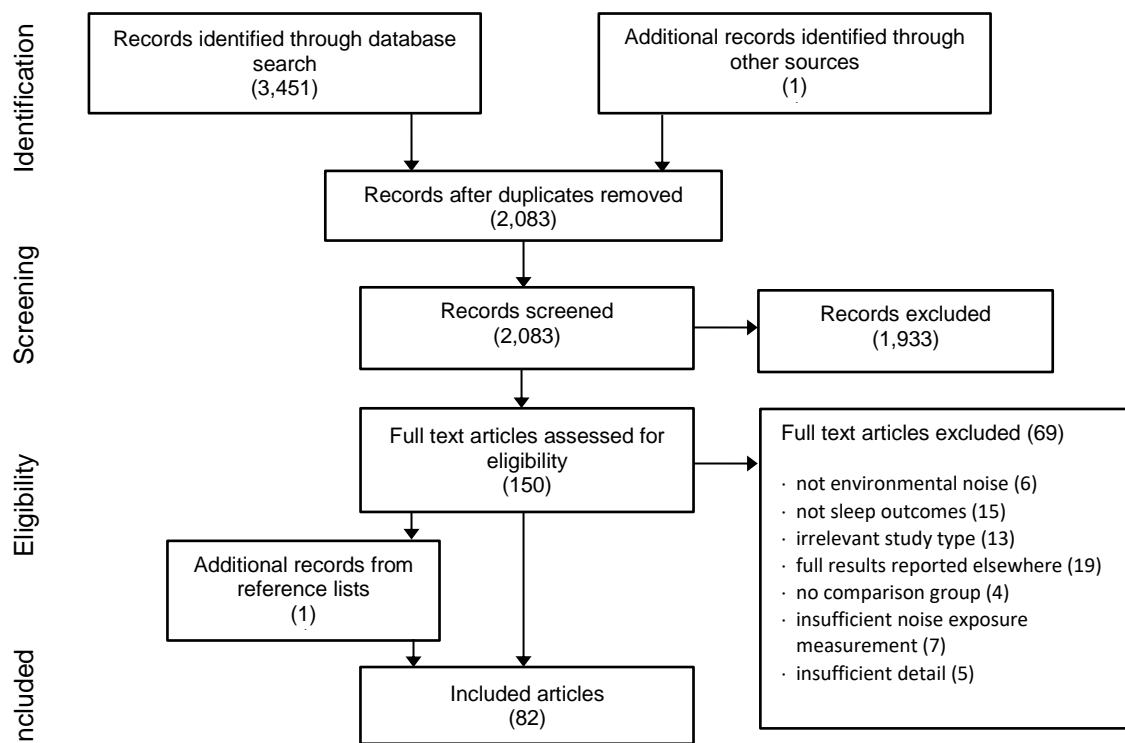


Figure 3-1: PRISMA flow chart – number of articles identified and reviewed during the systematic review (Moher et al. 2009)

3.2.2 Overview of included studies

Although outside the scope of this review, it is obvious that loud noises disrupt sleep. Loud noises are used throughout the world to disturb sleep as a method of studying its underlying functions.

Of the 82 articles identified, 79 were from distinct studies as some articles reported on the same data. Of these 79 studies, 43 were observational and 36 experimental. Most were observational studies (31 were cross-sectional studies (NHMRC level IV) and there was one prospective cohort study (NHMRC level II). There were eight field studies, where individuals had their sleep patterns and noise exposure monitored in their homes for several days. These were categorised as NHMRC level III-2 studies. Three studies included both a cross-sectional and field study component.

According to the NHMRC hierarchy of evidence (Table A-7), the experimental studies were either non-randomised experimental studies (31 studies, NHMRC level III-2) or pseudo-randomised studies (5 studies, NHMRC level III-1). Although many were non-randomised in design, several used counterbalancing to allocate participants to conditions and were thus rated as having a lower risk of bias (Table A-5). Most of these studies were done in temperature and sound-controlled sleep laboratory settings (32 studies). Some were done in the participant's home (7 studies) for some or all of the experimental period. Simulated noise was delivered via loudspeaker or personal music player with earphones.

3.2.3 Noise exposure and how it was measured

Observational studies explored: road traffic noise (29 studies), aircraft noise (8), railway noise (7), road work noise (1) and blast noise from a military base (1). Experimental studies simulated noise from: road traffic (21 studies), aircraft (9), railways (16) and road work (1).

For observational studies, noise exposure was measured by direct measurement with sound level meters in various locations (28 studies) or estimated using models or noise contour maps (17). In experimental studies, noise was delivered in such a way as to control the noise levels participants were exposed to.

The most common noise indicators used in the included studies were A-weighted equivalent sound levels (L_{Aeq}) for various periods. Maximum sound pressure levels (L_{Amax}) were also commonly used.

3.2.4 Types of outcomes reported

The included studies assessed a wide range of sleep outcomes. The most common were self-reported sleep disturbance outcomes (36 observational and 28 experimental studies). These included subjective assessments of problems falling and staying asleep, sleep duration, sleep quality/ disturbance ratings and feelings of tiredness/feeling well rested the next day.

Objective measures of sleep disturbance include activity trackers which can be referred to as actigraphy, actimetry or accelerometer (7 observational and 5 experimental studies) and polysomnography (4 observational and 22 experimental studies). These measure sleep parameters including arousals, gross bodily movement (motility) and sleep structure.

Other outcomes reported in these studies were the use of sleep medications (two observational studies) and prevalence or incidence of insomnia using International Statistical Classification of Diseases definitions (one observational study). One experimental study used an infrared pupillographic sleepiness test.

3.2.5 Quality ratings

Quality ratings according to GRADE criteria are shown in Table 3-1 to Table 3-3. These indicate that on aggregate, the quality of the evidence was rated as low.

All included studies are listed in section 8.3.

Table 3-1: GRADE evidence profile for environmental noise and sleep - Self-reported sleep disturbance (problems falling and staying asleep, sleep duration, quality/disturbance ratings, feelings of tiredness/or being well rested, and symptoms of insomnia)

No of studies (design)	Reasons for rating quality down	Reasons for rating quality up	Summary of key findings	Quality score
Thirty-two (cross-sectional)	Serious risk of bias	None	Exposure to road, rail and aircraft noise was associated with increased risk of sleep disturbance.	⊕⊕○○ Low
One (prospective cohort)	Serious risk of bias One small study	None	Self-reported sleep quality affected by road traffic noise, and significantly improved through noise abatement. Number of awakenings not affected by noise or noise abatement.	⊕⊕○○ Low

No of studies (design)	Reasons for rating quality down	Reasons for rating quality up	Summary of key findings	Quality score
Six (field studies)	Serious risk of bias Some inconsistency	None	Significant decreases in sleep quality and increased awakenings in participants exposed to high levels of night-time road traffic noise. Little to no effect of aircraft and rail.	⊕⊕○○ Low
Ten (experimental)	Some risk of bias Some inconsistency	None	Disruptions to sleep and poorer sleep quality are greater with increasing noise levels. Evidence was strongest for two aircraft noise studies.	⊕⊕⊕○ Moderate

Table 3-2: GRADE evidence profile - Objective sleep disturbance (actigraphy, polysomnography, accelerometer, Infrared pupillographic sleepiness test)

No of studies (design)	Reasons for rating quality down	Reasons for rating quality up	Summary of key findings	Quality score
Eleven (field studies)	Serious risk of bias Serious inconsistency	None	Increasing sleep stage changes and motility with maximum levels of aircraft and rail noise. Mixed results for road noise.	⊕⊕○○ Low
Twenty-six (experimental)	Some risk of bias Some inconsistency	None	Noise significantly changed sleep structure with less slow wave sleep, greater latency to slow wave sleep, more arousals and sleep stage changes.	⊕⊕⊕○ Moderate

Table 3-3: GRADE evidence profile for environmental noise and sleep - Use of sleep medication (self-report)

No of studies (design)	Reasons for rating quality down	Reasons for rating quality up	Summary of key findings	Quality score
Two (cross-sectional)	None	None	Increasing aircraft and railway noise levels associated with increased risk of sleep medication use.	⊕⊕○○ Low

3.3 Summary of findings from the systematic review

3.3.1 What is the evidence of a causal effect of environmental noise on sleep disturbance?

This systematic review identified 79 studies published between 1994 and 2014 examining the relationship between environmental noise exposure and sleep disturbance. A total of 43 of these studies were observational and 36 experimental.

A particular issue in sleep studies is the problem of blinding participants or outcomes assessors to the condition being tested. This is coupled with the problem of defining what constitutes disturbed sleep.

Subjective measures may provide a better indication of when sleep has been notably disturbed but suffers from bias because of the blinding issue.

Objective measures tend to derive from highly sensitive physiological measures such as collected by polysomnography and it remains unclear what sized effect, if any, perturbations in many of these measures means for people's health, or annoyance levels.

Many of the measurements of sleep may be too sensitive for a person to even notice and may be below their level of a just-noticeable difference.

Another issue is the heavy reliance on laboratory based experiments in sleep and noise research. These can be designed with better scientific rigour but this always comes at a cost to the external validity of the study as the participants are often heavily screened and do not represent the population as a whole. The participants are also not sleeping in their own environments, which may influence their response to noise either positively or negatively.

3.3.2 Observational studies

Several studies below examined more than one noise source.

Aircraft noise

Eight studies examined the associations between aircraft noise exposure and sleep disturbances. All indicated that aircraft noise was associated with poorer sleep.

Road traffic noise

A total of 28 studies examined the associations between exposure to road traffic noise and sleep disturbances. Most of these (21 of 28) indicated that higher noise levels were linked with poorer sleep. The rest found non-significant results.

Rail noise

Seven studies examined the relationship between railway noise and sleep disturbance. Six reported a significant relationship between rail noise and sleep disturbance, with one reporting non-significant results. Most assessed both freight and passenger rail noise in the study.

Other noise sources

Three studies examined other relevant environmental noise sources such as general community noise and noise from military areas. All found that higher levels of noise were linked with poorer sleep.

Study limitations

Despite the consistency of these findings, the quality of the evidence provided by these studies was determined to be low. This low quality rating reflects issues relating to study design (such as predominantly cross-sectional studies), and high risk of bias (primarily due to measurement of sleep and control of confounders). These issues are detailed below and limit our ability to draw definitive conclusions about the effects of environmental noise on sleep.

For the study design, most of the observational studies (34 out of 43) were cross-sectional (NHMRC level of evidence: IV). Although most of these reported significant relationships between environmental noise and sleep, they are not able to provide insight into the causal effect of noise on sleep. Further, 18 of the 34 cross-sectional studies had a high risk of bias and 13 had moderate risk of bias. Only two studies were rated as having a low risk of bias (Halonen et al., 2012; Kim et al., 2014). The large number of studies with moderate or high risk of bias was primarily due to self-reported measures of sleep (27 out of 34 studies) and inadequate control of relevant confounding variables (22 out of 34 cross-sectional studies). The Lundby tunnel study (Öhrström, 2004; Öhrström and Skanberg, 2004) was the only prospective cohort study in this review. It was rated as having a high risk of bias due to self-reporting measures of sleep and lack of control for potential confounders.

The eight field studies (NMHRC level of evidence: III-2) give better insight into the causal nature of the relationship between noise exposure and sleep disturbance. This is because these studies provide an indication of the concurrent relationships between noise exposure and sleep in the usual sleep environment. The immediate effects of noise exposure on sleep outcomes can therefore be assessed in these studies. However, only two of the eight studies had a low risk of bias. Of the remaining studies, three had a moderate risk of bias and three had a high risk of bias. The main issues underlying the moderate and high risk of bias were self-reported measures of sleep and inadequate control.

Some further issues in methodology require discussion. It was difficult to draw clear conclusions from these studies due to the large variation in the sleep outcomes assessed. For example, the types of sleep outcomes assessed included sleep disturbance, sleep quality, insomnia symptoms, night-time awakenings, daytime dysfunction, and use of sleep medication, sleep stages and sleep efficiency. This was further compounded because most sleep outcomes were based on self-reporting measures only, with a large number of studies using single-item measures of sleep quality. These measures lack validity compared with objective measures and have the potential to lead to imprecise estimates on the relationship between noise and sleep. These issues suggest that caution is needed when interpreting the results of the observational evidence base.

The noise exposure indicator is relatively consistent across studies (usually L_{Aeq} or L_{Amax}). However, studies varied considerably in how the noise exposure was estimated (such as direct measurement or contour maps) and the site at which it was measured (such as at building façade or the participant's ear). This complicates the synthesis of the evidence.

Similarly, within the studies it is important to distinguish between façade noise levels, often used in Australia and France, and the free field noise levels often used in other countries. Free field noise levels account only for noise coming from a source. Façade levels account for both noise coming from a source and noise reflected back from a façade. A façade level is typically 2.5 to 3.0 dB higher than the corresponding free field.

Studies with a low risk of bias

Only two cross-sectional (Halonen et al., 2012; Kim et al., 2014) and two longitudinal studies (Basner et al., 2006; Frei et al., 2014) had a low risk of bias. The results of these are briefly outlined below.

Halonen et al. (2012) conducted a cross-sectional study of 7019 adults and found that symptoms of insomnia were significantly higher when road traffic noise measured at a residential façade exceeded L_{night} 55 dB (odds ratio (OR) = 1.32 [1.05 – 1.65]). Kim et al. (2014) examined the relationship between exposure to aircraft noise (from a military airport) and sleep quality in a sample of 1982 adults. The results indicated that noise levels (Weighted Equivalent Continuous Perceived Noise Level measured externally) between 60 and 80 dB (OR = 2.61 [1.58 – 4.32]) and > 80 dB (OR = 3.52 [2.03 – 6.10]) were linked with disturbed sleep.

Basner et al. (2006) conducted an experimental field study of 64 adults. They found that aircraft noise events that were above 33 dB (measured at the ear) were associated with increased awakenings. Frei et al. (2014) conducted a study of 1122 adults comparing sleep disturbance using a standardised sleep disturbance score with modelled road traffic noise. This study found that road traffic noise levels > 55 dB L_{Aeq} (measured at the residential façade) were associated with a greater prevalence of sleep disturbance.

3.3.3 Experimental studies

There were 36 experimental studies examining the relationships between environmental noise exposure and sleep outcomes. Several studies examined multiple noise sources, such as road, rail and air.

Most studies indicated that exposure to environmental noise was significantly associated with sleep disturbances.

Aircraft noise

Nine studies examined the effects of aircraft noise exposure and sleep disturbances. All indicated that aircraft noise led to poorer sleep.

Road traffic noise

Twenty one studies examined the effect on sleep of exposure to road traffic noise. Most (15 out of 21) indicated that higher noise levels were linked with poorer sleep. The rest reported non-significant results.

Rail noise

Sixteen studies examined the effects of rail noise on sleep disturbance. Most (15 out of 16) reported significant deleterious effects of noise on sleep. Most assessed both freight and passenger rail noise within the study.

Other noise sources

Only one study investigated the effects of construction noise. It found that higher noise levels were associated with poorer sleep.

Study limitations

The experimental studies have higher level of evidence ratings (NHMRC), and thus provide an important insight into the effects of noise on sleep. In general, these studies had lower risk of bias compared with the observational studies. For example, nine studies had a low risk of bias and 14 had a moderate risk of bias. About one third of the experimental studies (13 studies) had a high risk of bias.

The main factors underlying moderate and high risk of bias reflect the lack of randomisation to conditions or the lack of counterbalancing. Several studies did not blind participants and outcome assessors to the condition allocation, which could also increase the risk of bias, noting that it is difficult to blind participants to noise conditions. Although many studies used objective measures of sleep, several relied on self-reported measures. In combination with the issues raised above, the often small sample sizes (such as those less than 10) contributed to an elevated risk of bias.

The wide variety of sleep outcomes examined also makes it difficult to draw clear conclusions about the effects of noise on sleep. The lack of prospective study registration in this field makes it impossible to gauge the extent of selective reporting of outcomes. Although most experimental studies used polysomnography, the specific sleep parameters varied. These parameters included sleep duration, sleep efficiency, sleep stages, sleep-stage transitions, sleep latency, time in rapid eye movement (REM) sleep and sleep spindles.

The implications of many of these outcomes (such as sleep spindles and sleep stage transitions) are yet to be determined. This means the implications of some findings for sleep disturbance are not clear.

Although the experimental studies generally had a lower risk of bias compared with the observational studies, many of them may lack external validity. This is particularly the case for those studies that assessed sleep in laboratory settings. The results of these studies may not provide a valid indication of the effects of noise on sleep in a real world setting.

3.3.4 Studies with a low risk of bias

All of the nine studies with a low risk of bias indicated that exposure to various sources of noise was linked with disturbed sleep. For example, Schapkin et al. (2006a) examined the effects of rail noise on sleep assessed via polysomnography and self-reporting in a sample of 22 adults. The results showed that increasing rail noise (from quiet to L_{Aeq} 50 dB(A)) measured at the ear was linearly associated with poorer subjective sleep.

Schapkin et al. (2006b) examined the effects of nocturnal aircraft noise measured at the ear on self-reported sleep. The results indicated that subjective sleep quality linearly worsened with increasing aircraft noise levels (from quiet to L_{Aeq} 50 dB(A)).

Basner and Samel (2005) examined sleep in 128 subjects (16 controls) across 13 consecutive nights. Their results indicated that exposure to aircraft noise measured at the ear was significantly associated with some indicators of disturbed sleep. This included increased awakenings and alterations to sleep architecture resulting in less slow wave sleep and more stage 1 light sleep.

Subsequent analysis suggested these associations became apparent only at maximum sound pressure level (SPL) at or above 50 dB(A) (awakenings), at or above 55 dB(A) (increased stage 1 light sleep), and at or above 65 dB(A) (decreased slow wave sleep). The analysis also suggested these associations were significant only when the number of aircraft noise events was greater than or equal to eight (increased awakenings), 16 (reduction in slow wave sleep), and 64 (increased stage 1 light sleep).

3.3.5 Summary of the evidence

The observational and experimental studies together indicate a significant relationship between exposures to higher levels of environmental noise and sleep disturbances. However, the issues in method noted above and variations in study design makes it difficult to draw definitive conclusions from the evidence base.

The quality of the evidence was rated as low for the observational studies given the large number of cross-sectional studies and the high risk of bias. The experimental studies generally provided better quality evidence.

Both observational and experimental studies assessed a wide range of sleep parameters using various measures.

Many studies used both objective and subjective measures of sleep disturbance. Noise was found to exert a larger effect on self-reported sleep compared with objectively assessed sleep. One mediating factor may be that annoyance caused by noise may cause sleep disturbance and extended awakening. Some individuals may therefore over-report the effects of noise on the quality of their sleep. Some studies using a combination of objective and subjective measures found effects for self-reported sleep but no or very weak effects for polysomnography-assessed sleep. Examples include the study by Schapkin et al., 2006a. This suggests that the effects of environmental noise are overestimated in those studies using self-reported sleep measures.

3.3.6 Is there a dose–response relationship between environmental noise and sleep disturbance?

Many observational studies demonstrated that sleep disturbances become more pronounced as noise level increases (e.g. Banerjee, 2013; Bluhm et al., 2004; Boes et al., 2013; de Kluizenaar et al., 2009; Franssen et al., 2004; Frei et al., 2014; Kim et al., 2014).

The precise measures of sleep varied considerably between studies, as did the quantification of noise exposure. For example, Boes et al. (2013) examined the effects of a 1 dB(A) increase in

noise, de Kluizenaar et al. (2009) broke noise exposure into 10 dB(A) categories, and Frei et al. (2014) assessed four noise exposure groups (< 30 dB(A), 30 – 40 dB(A), > 40 – 55 dB(A), and > 55 dB(A)). This lack of consistency means it is possible to conclude that observational studies show a dose–response relationship, but the precise nature of the relationship cannot be determined easily.

Several experimental studies also indicated a dose–response relationship between noise exposure and sleep disturbance (e.g. Basner and Samel, 2005; Kawada and Suzuki, 1995; Schapkin et al., 2006a). Again, major methodological differences between studies make it difficult to combine studies. Studies were also difficult to compare due to the varying noise metrics used.

As an example, L_{den} is a noise metric that describes a hybrid of noise over the day, evening and night. It could be argued that the day and evening parts are irrelevant to sleep (unless the subjects sleep during the day). A night-time level would be more helpful. Also, L_{Aeq} is a noise metric that effectively describes noise as an average over an extended period. Particularly in the case of aircraft and train noise, it depends on the number of noise events and their specific noise levels.

Reported thresholds are outlined below for each of the three main noise sources.

Road traffic noise

Seven observational studies examined the effects of road traffic noise and found significant impairments in sleep quality associated with noise levels measured at the exterior façade above 55 dB L_{night} (Banerjee, 2013; Halonen et al., 2012; Ristovska et al., 2009) and 55 dB L_{Aeq} (Frei et al., 2014; Kristiansen et al., 2011; Lercher and Kofler, 1996; Yoshida et al., 1997)

Several experimental studies also reported significant effects of peak or equivalent noise levels at or above 45 dB(A) (Kawada and Suzuki, 1999; Kuwano et al., 2002).

Rail noise

Two observational studies examining rail noise found significant relationships with sleep disturbances at noise levels measured at the exterior façade of ≥ 60 dB L_{Aeq} (Aasvang et al., 2008) and ≥ 60 dB L_{den} (Lercher et al., 2010).

Experimental studies indicated that the effects of rail noise on sleep were observed at lower levels, with several studies finding effects above 50 dB(A) (Kaku et al., 2004; Saremi et al., 2008; Bonnefond et al., 2008) and 54 dB(A) (Griefahn and Robens, 2010).

Aircraft noise

Two observational studies indicated that threshold effects for aircraft noise were comparatively low at 32 dB $L_{Aeq,night}$ (Passchier-Vermeer et al., 2002) and 33 dB L_{ASmax} (Basner et al., 2006).

Experimental studies indicated some effects of aircraft noise at 39 dB(A) (Schapkin et al., 2006b) and 45 dB(A) (Basner et al., 2008), but effects were reported to be most evident at higher levels (for example, > 50 dB(A) or ≥ 65 dB(A)).

3.3.7 Is there any evidence that certain populations are vulnerable to the effects of environmental noise on sleep disturbance?

Only a small number of studies formally investigated whether the relationships between environmental noise and sleep disturbance were more pronounced in certain populations.

Halonen et al. (2012) found the effects of road traffic noise on insomnia symptoms were more pronounced in individuals with higher levels of self-reported anxiety traits. Bjork et al. (2006) found the effects of road traffic noise on self-reported sleep disturbances were greater in individuals with higher levels of annoyance and in individuals born overseas.

This raises the possibility that some effects may be greater in certain populations, but there is not sufficient evidence to draw strong conclusions on this.

3.3.8 Does the association between environmental noise and sleep disturbance vary by noise source?

Few studies compared whether the influence of noise on sleep disturbance varied depending on the source. Studies tended to examine one source, such as aircraft or road traffic noise. With little consistency in methods, such as sample characteristics, noise levels and experimental conditions, it is not possible to meaningfully compare results.

However, a small number of studies did compare the effects of different sources of noise. Griefahn et al. (2006b) compared the effects of aircraft, rail and road noise. Their results indicated similar effects from the sources of noise, although the effects appeared greatest for rail noise. Aasvang et al. (2011) compared the effects of road traffic noise with railway noise. The results indicated that railway noise had a greater effect on rapid eye movement (REM) sleep compared with road traffic noise. This suggests that railway noise may have a larger effect on sleep outcomes.

Basner et al. (2011) provided further insight into the nature of these differences in an experimental study that compared the effects of rail, road and aircraft noise on sleep parameters. Interestingly, the nature of the differences between noise sources varied depending on whether sleep was assessed via polysomnography or self-reported.

When polysomnography was examined, road traffic noise had the largest effects on sleep structure and continuity. However, when self-reporting measures were used, aircraft and rail noise were found to have a larger effect on sleep compared with road traffic noise (Basner et al., 2011).

Basner et al. (2011) suggested that because road traffic noise events are relatively short they were perceived as having less effect on sleep. In other words, the events were not long enough for participants to consciously perceive their sleep was affected.

In contrast, rail and aircraft noise typically last longer and so may be more likely to be perceived as having affected sleep. Basner et al. (2011) attributed the greater effects of road traffic noise on polysomnography-assessed sleep parameters to the specific acoustic properties of road traffic noise, such as faster sound pressure level rise time and greater energy in the high-frequency octave bands compared with aircraft noise.

It is plausible that aircraft, rail and road traffic noise have differential effects on sleep quality. However, because available data is limited it is not possible to draw definitive conclusions on the nature and magnitude of these differences.

3.3.9 Is there any evidence that annoyance is a mediator linking environmental noise exposure to sleep disturbance?

Annoyance is discussed by a large number of studies as a likely mechanism linking environmental noise exposure with poor sleep, particularly self-reported sleep. Some studies examined both annoyance and sleep disturbance as an outcome, but there is no evidence that studies have formally examined whether annoyance is a mediator linking noise exposure with sleep disturbance.

Frei et al (2014) found that annoyance was strongly related to self-reported sleep measures; actigraphy and diaries were used to assess sleep in a nested sub-group of this study. It was reported that measured sleep efficiency was more strongly associated with modelled noise exposure than with self-reported annoyance. This suggests annoyance is a mediating factor for

subjective sleep complaints but not an objective measure for noise. It is possible that annoyance is a mechanism linking noise exposure with poor sleep. But it is not clear if these effects are limited to self-reported or objective assessment of sleep. Because of the lack of formal investigation, it is not possible to draw any definitive conclusion on the role of annoyance in the environmental noise-sleep disturbance literature.

3.4 Conclusions

Some studies suggest a dose–response relationship between noise and physiological effects on sleep. The systematic review identified 79 studies and sub-studies published between 1994 and 2014 that examined the associations between exposure to different forms of environmental noise and sleep disturbances. In general, the results of these studies are consistent in indicating that exposure to sources of environmental noise (mainly road traffic, rail and aircraft noise) are associated with sleep disturbances.

Overall the quality of the studies in this review was low, reflecting study design, risk of bias, and inconsistency in outcome measures. As a result, an NHMRC rating statement of C is applied to the overall body of evidence (see rating criteria in appendix A). The body of evidence from this systematic review has limitations and care should be taken in interpreting the findings.

4 NOISE AND CARDIOVASCULAR DISEASE

4.1 Introduction and background

Cardiovascular disease encompasses all conditions and diseases affecting the heart and blood vessels (AIHW, 2014a). In Australia, coronary heart disease, stroke and heart failure are the most common forms (AIHW, 2014a).

Although the incidence of cardiovascular disease has declined in Australia over the past two decades (AIHW, 2014a), it is estimated that 22 per cent of the adult population has some form of the disease. It remains the major cause of death in Australia, accounting for 31 per cent of all deaths, and second only to cancer as the largest contributor to total burden of disease (AIHW, 2014b). There are many risk factors for cardiovascular disease, including age, sex and genetics, as well as modifiable risk factors such as overweight/obesity, sedentary lifestyles, unhealthy diet, smoking and alcohol consumption (AIHW, 2009).

There has also been considerable interest in the role of environmental factors such as air pollution and noise in increased risk of cardiovascular disease. The World Health Organisation estimates that around 1.5 million ischemic heart disease deaths occur globally each year (based on 2012 estimates) due to ambient air pollution (WHO, 2014). Although there are no global estimates of the impacts of environmental noise on ischemic heart disease, regional estimates for Western Europe indicate that the burden is large at 61,000 Disability Adjusted Life Years (DALYs) a year. This is around 1.8 per cent of all ischemic heart disease DALYs attributable to transport noise (WHO, 2011).

Research since the late 1960s suggests that exposure to different forms of environmental noise is linked with a greater risk of cardiovascular disease and changes in indicators of cardiovascular health, such as heart rate and blood pressure (Babisch et al., 1990; Knipschild, 1977). Many subsequent studies have further examined these relationships and some reviews of the evidence have been conducted (Babisch, 2006).

4.2 Systematic review of the literature

A systematic review of the literature was conducted for studies investigating the relationship between environmental noise and cardiovascular disease for the period January 1994 to March 2014. This is further detailed in appendix A.

4.2.1 Search results

Details of the results of the search process are summarised in the following PRISMA flow chart.

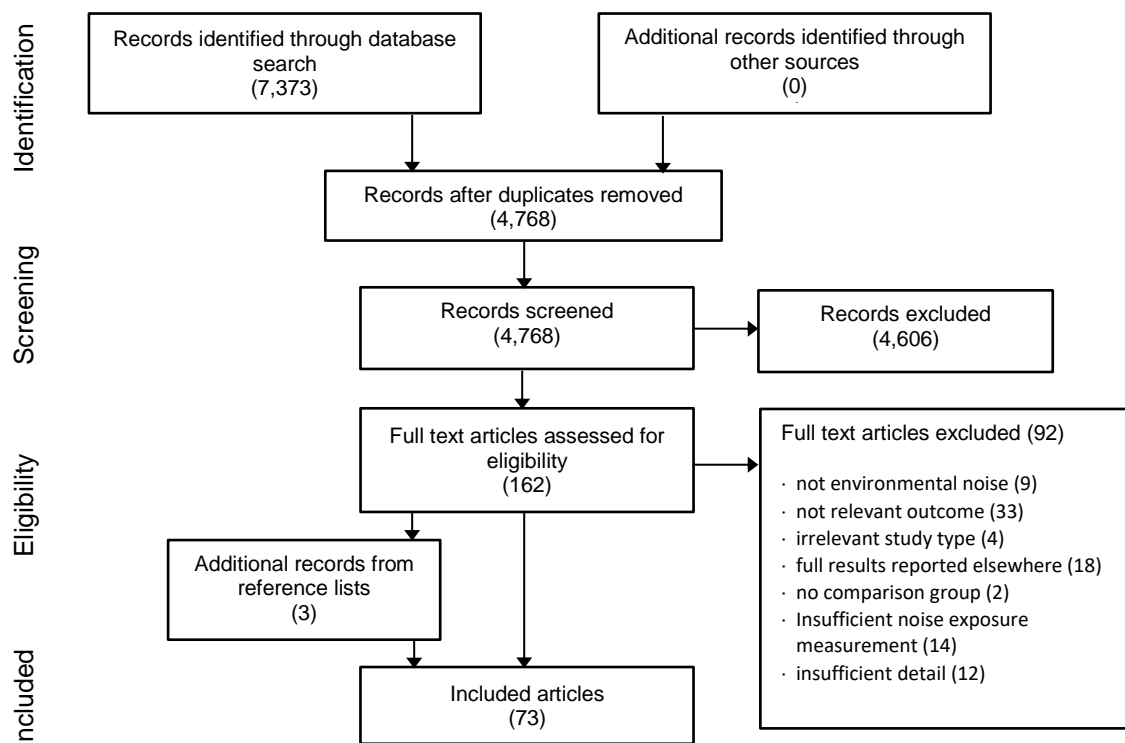


Figure 4-1: PRISMA flow chart. Number of articles identified and reviewed during the systematic review (Moher et al. 2009)

4.2.2 Overview of included studies

Of the 73 articles identified, 65 were from distinct studies (some reported on the same data); 62 were observational designs, while three were experimental. The majority of observational studies (40) were cross-sectional studies (NHMRC level IV). Some studies had multiple components with different methods, such as cross-sectional and prospective cohort components.

There was also a small number (10) of prospective cohort studies (NHMRC level II), ecological studies (five) (NHMRC level IV), case-control studies (four) (NHMRC level III-3) and field studies (three) (NHMRC level III-2).

All of the experimental studies were non-randomised experimental studies (three) (NHMRC level III-2). One was conducted in a sleep laboratory, one in a sound and temperature-controlled room and one in a park setting.

4.2.3 Noise exposure and how it was measured

Observational studies explored road traffic noise (42), aircraft noise (19), railway noise (seven), and general environmental noise (five). Experimental studies addressed the effects of road traffic (three), and aircraft noise (one) on cardiovascular disease. Several studies examined multiple sources of noise.

For observational studies, noise exposure was measured by direct measurement with sound level meters (17 studies) or estimated using models and contour maps (39 studies). Six studies used a combination of direct measurement and models/contour maps, while three did not clearly specify the measurement approach. Noise was measured using sound level meters in all three experimental studies.

The most common noise indicators used were A-weighted equivalent sound levels (L_{Aeq}) for various periods. Maximum sound pressure levels (L_{Amax}) were also commonly used.

4.2.4 Types of outcomes reported

A breakdown of the cardiovascular disease outcomes in these studies is:

- hypertension/blood pressure (45 studies)
- cardiovascular disease mortality (3 studies)
- ischemic heart disease and myocardial infarction (16 studies)
- stroke (6 studies)
- other relevant outcomes such as diabetes and aortic calcification (4 studies).

The measures used to assess these outcomes varied considerably. For example, a range of self-reported diagnoses and direct measurements of blood pressure were used across studies.

Note that several studies examined multiple cardiovascular disease outcomes.

4.2.5 Quality ratings

GRADE is a structured process for rating quality of evidence in systematic reviews. Quality ratings according to GRADE criteria are shown in Table 4-1. This indicates that on aggregate, the quality of the evidence was rated as low.

All included studies are listed section 8.4. GRADE criteria are detailed in appendix A.

Table 4-1: GRADE evidence profile for environmental noise and cardiovascular diseases (65 studies)

No of studies (design)	Reasons for rating quality down	Reasons for rating quality up	Key findings	Quality score
Cardiovascular disease mortality				
One (ecological)	None	None	Increased risk of death from myocardial infarction in people exposed to aircraft noise over 60 dB(A) especially those exposed >15 y	⊕⊕○○ Low
Three (prospective cohort)	None	None	High levels of transportation noise (≥ 65 dB(A)) associated with elevated risk of mortality.	⊕⊕⊕○ Moderate
Ischaemic heart disease and myocardial infarction (self-report)				
Four (cross-sectional)	Serious inconsistency	None	Road traffic noise may be associated with greater self-reported heart disease and stroke but confounding of air pollution may be an issue.	⊕○○○ Very low
Ischaemic heart disease and myocardial infarction (hospital record)				

No of studies (design)	Reasons for rating quality down	Reasons for rating quality up	Key findings	Quality score
Three (cross-sectional and ecological)	Serious risk of bias Serious inconsistency	None	Small association found between road traffic noise and hospitalisations for myocardial infarction. Aircraft noise may have small impact on hospitalisations for cerebrovascular disease, ischaemic heart disease and heart failure.	⊕⊕○○ Low
Three (prospective cohort)	Some inconsistency	None	Road traffic noise not significantly associated with ischaemic heart disease or cerebro-vascular disease. May have a small impact on myocardial infarction.	⊕⊕⊕○ Moderate
Four (case control)	Serious inconsistency	None	Mixed results for road traffic noise. May have small impact on hospitalisations for myocardial infarction, particularly in males at very high equivalent sound levels (>70 dB(A)).	⊕⊕⊕○ Moderate
Stroke (self-report)				
One (cross-sectional)	Serious risk of bias Serious inconsistency Stroke not analysed separately from other cardiovascular heart disease outcomes. One small study	None	No significant findings.	⊕○○○ Very low
Stroke (hospital records)				
One (ecological)	Some risk of bias Only one study	None	Aircraft noise at high equivalent sound levels may have a small effect on hospitalisations for stroke.	⊕○○○ Very low
One (prospective cohort)	Only one study	None	Road traffic noise (L_{den}) at very high levels may have small effect on hospitalisations for older people (≥ 64 y).	⊕⊕⊕○ Moderate
Hypertension (measured)				
Twelve (cross-sectional)	None	None	Road traffic noise not significantly associated with hypertension.	⊕⊕○○ Low
Two (prospective cohort)	Some risk of bias	None	Aircraft noise may be associated with increased hypertension in older males.	⊕⊕○○ Low
Hypertension (self-report)				
Sixteen (cross-sectional)	Serious risk of bias Serious inconsistency	None	Higher exposure to road traffic noise associated with increased self-reported hypertension.	⊕⊕○○ Low

No of studies (design)	Reasons for rating quality down	Reasons for rating quality up	Key findings	Quality score
Four (prospective cohort)	Serious risk of bias Serious inconsistency	None	Higher exposure to road traffic noise associated with increased self-reported hypertension.	⊕⊕○○ Low
Type 2 diabetes insulin levels (hospital records)				
One (prospective cohort)	Only one study	None	Road traffic noise may slightly increase risk of hospitalisation. No effect from rail noise.	⊕⊕⊕○ Moderate
One (experimental)	Serious risk of bias Only one small study	None	Insulin levels may be sensitive to road traffic noise.	⊕○○○ Very low
Blood pressure and heart rate				
Fifteen (cross-sectional)	Moderate risk of bias Some inconsistency	None	Road and aircraft noise significantly associated with increased systolic blood pressure, particularly in children.	⊕⊕○○ Low
Four (prospective cohort)	Serious risk of bias Serious inconsistency	None	Mixed results. Blood pressure is sensitive to changes in noise levels.	⊕⊕○○ Low
Two (field experimental)	None	None	During sleep aircraft noise events (L_{max}) had an effect on blood pressure and dipping in diastolic blood pressure. No effect on heart rate. Maximum noise level, not noise type (such as road or air) was most important.	⊕⊕○○ Low
One (experimental studies)	Serious risk of bias One small study	None	Walking through a noisy or quiet park made little difference to blood pressure and heart rate.	⊕⊕○○ Low
Cardiac arrhythmia				
One (experimental)	Serious risk of bias One small study	None	No effect of air and road traffic noise on cardiac arrhythmia.	⊕○○○ Very low
Coronary artery atherosclerosis and calcification				
Two (cross-sectional)	Serious risk of bias Serious inconsistency	None	Higher quality study suggests a small effect of road traffic noise on atherosclerosis.	⊕⊕○○ Low

4.3 Summary of findings from the systematic review

4.3.1 What is the evidence of a causal effect of environmental noise on cardiovascular health?

A total of 65 studies examining the relationship between environmental noise and cardiovascular outcomes were included in this review. Most of these studies were observational (62), with only three experimental studies identified. The findings for the observational and experimental studies are summarised below.

4.3.2 Observational studies

Aircraft noise

A total of 19 observational studies examined the associations between aircraft noise and various cardiovascular outcomes. Most studies (15) reported a significant relationship between exposure to aircraft noise and adverse cardiovascular outcomes in the total sample (14 studies) or in sub-groups (1 study). These studies indicated that exposure to aircraft noise was significantly associated with hypertension, increased blood pressure, hospitalisations for cardiovascular diseases, use of medications for hypertension and other cardiovascular disease and cardiovascular mortality. Only three studies reported no significant associations between aircraft noise exposure and cardiovascular health.

Road traffic noise

Forty-three observational studies examined the relationships between exposure to road traffic noise and cardiovascular outcomes. The evidence in these studies was mixed. A total of 21 studies reported that increased road traffic noise was significantly associated with adverse cardiovascular outcomes. One found a significant result in the opposite direction, with increased noise associated with lower systolic blood pressure in children (van Kempen et al., 2006). A further nine studies found no significant effect in the total sample, but evidence of associations in sub-groups such as certain age or gender groups. Twelve studies reported no significant associations between road traffic noise and cardiovascular outcomes.

Rail noise

The associations between rail noise and various cardiovascular outcomes were examined in seven studies. One of these studies indicated that greater railway noise was associated with hypertension (Dratva et al. 2012). One study indicated that railway noise was associated with hypertension but not stroke or diabetes (HYENA; Sørensen et al., 2011a, 2011b, 2013). One found that rail noise was associated with self-reported hypotension in females under the age of 42 (Lercher and Widmann, 2013). Another four reported no significant association between railway noise and cardiovascular outcomes.

General environmental noise

Five studies examined general environmental and community noise exposure. Except for one study (Lepore et al., 2010), all indicated that greater noise exposure was associated with poorer cardiovascular health.

Study limitations

There are some important limitations of the observational studies. A key limitation is that most of the observational studies were cross-sectional (NHMRC level of evidence: IV) and are unable to provide an indication of the direction of causation. Although there were several prospective, case-control, and field studies, the results were mixed. This limits conclusions on the temporal effect of environmental noise on cardiovascular health.

While the type of noise exposure indicator used was relatively consistent across the studies (usually L_{Aeq} or L_{Amax}), there was considerable variation in how the noise exposure was estimated, such as using direct measurement or contour maps. There was also variation in the location at which the measurements were taken, such as at the building façade or participant's ear, complicating the synthesis of evidence.

There were also considerable differences between studies in the types of cardiovascular outcomes examined and the measures used to assess them. Cardiovascular outcomes assessed included: incidence of hypertension, stroke, heart disease or diabetes; treatment of hypertension; hospital records; mortality data; and aortic calcification. This variation makes it difficult to draw clear conclusions about the effect of environmental noise on cardiovascular health. These issues are compounded because the observational studies differed in whether cardiovascular outcomes were assessed using self-reporting or objective measures. A large number of studies examined self-reported hypertension, which is less accurate than an objective measure of hypertension based on blood pressure measurements. Many middle and older-aged adults may have undiagnosed hypertension, which would not be reflected in these self-reported measures. Therefore, self-reporting measures can limit the validity of findings and contribute to risk of bias.

There is also considerable potential for residual confounding, given that many studies did not control for relevant covariates such as air pollution. This is important as some studies found that an association between noise exposure and cardiovascular outcomes became non-significant when air pollution was added as a covariate (for example, Babisch et al., 2014a). Failure to control for these covariates could lead to false positive associations between noise exposure and cardiovascular health.

Twenty studies were rated as having a low risk of bias, 22 a moderate risk, and 21 a high risk. The primary reasons for moderate and high risk related to the use of self-reported measures of cardiovascular health and lack of control for relevant confounding variables.

Studies with a low risk of bias

The 20 studies with low risk of bias generally indicated that environmental noise exposure was linked with poorer cardiovascular health, although some findings were mixed. For example, several of the studies with a low risk of bias found non-significant results. Babisch et al. (1994) conducted a prospective case-control study of 4035 male adults and found that day-time exposure to road traffic noise ($L_{Aeq,6-22hours}$, exposure range 40 – 65 dB(A)) was not significantly associated with myocardial infarction incidence. In a prospective study of 18,213 adults, de Kluizenaar et al. (2013) found that road traffic noise (L_{den} at most exposed façade, per 10 dB increase) was not associated with cardiovascular disease hospitalisations. Foraster et al. (2011) found that road traffic noise (L_{night} and $L_{Aeq,24h}$ measured at the most exposed façade, per 10 or 5 dB increase) was not associated with hypertension in a cross-sectional study of 3480 adults. De Kluizenaar et al. (2007) found that road traffic noise (L_{den} at most exposed façade, per 10 dB increase) was not associated with use of antihypertensive medication. However, a significant effect was observed in adults aged 45 to 55 (odds ratio (OR) = 1.39 [1.08, 1.77]) at higher noise exposure ($L_{den} > 55$ dB). Clark et al. (2012) found that daytime road traffic and aircraft noise ($L_{Aeq,16h}$) were not associated with measured blood pressure in a sample of 351 children.

Other studies with a low risk of bias suggest a relationship between environmental noise and adverse cardiovascular outcomes. For example, Babisch et al. (2014a) conducted a cross-sectional study of 4166 adults and found that noise (L_{den} at exposed façade, per 10 dB increase) was not associated with hypertension but was associated with higher systolic blood pressure (OR per 10 dB(A) increase in noise = 1.43 [1.10, 1.86]). Selander et al. (2009) conducted a case control study of 3666 adults. Road traffic noise ($L_{Aeq,24h} \geq 50$ dB(A)) was not associated with

myocardial infarction risk in the total sample but a significant effect was observed in participants without hearing loss and a history of exposure to other noise sources (OR = 1.38 [1.11, 1.71]). Gan et al. (2012) conducted a prospective study of 466,727 adults and found that combined rail, air and road noise (postcode level L_{den} , range) was associated with cardiovascular disease mortality (OR per 10 dB(A) = 1.09 [1.01, 1.18]). In the diet, cancer and health cohort study, a prospective study of 57,053 adults, road traffic noise (L_{den} at most exposed façade, range) was associated with stroke (OR = 1.14 [1.03, 1.25]) and diabetes (OR = 1.11 [1.05, 1.18]).

4.3.3 Experimental studies

The findings of three experimental studies were included in this systematic review. Carter et al. (1994) examined the effects of exposure to aircraft and road traffic noise under laboratory conditions. The results indicated noise was not significantly associated with cardiac arrhythmia. Tomei et al. (2000) examined the effects of exposure to road traffic noise on levels of insulin under laboratory conditions. The results indicated that higher noise levels were significantly associated with increases in insulin levels. Finally, Janssen et al. (2012) conducted a field-based study examining the effects of exposure to road traffic noise on heart rate and blood pressure and did not find any significant results. The risk of bias for these studies was high, which primarily reflected issues relating to lack of control groups.

This review identified a number of experimental studies examining cardiac-related outcomes that were not relevant to this review because they focused on cardiac responses to noise during sleep. Rather than indicating an adverse effect on cardiac health, these cardiac responses most likely reflect an arousal response during sleep, perhaps indicative of awakening. These outcomes were therefore not considered relevant to cardiovascular health. Several studies also examined the effects of noise exposure on levels of hormones related to cardiovascular health, such as cortisol. Although these hormones are important, they are not considered cardiovascular disease outcomes, but rather part of the causal pathways linking noise and cardiovascular health.

4.3.4 Summary of the evidence

As noted above, most studies examining the associations between environmental noise exposure and cardiovascular outcomes have been observational. These results suggest that exposure to environmental noise is associated with poorer cardiovascular outcomes. The most consistent findings were observed for aircraft noise, while several studies indicated an association between road traffic noise and cardiovascular health. Use of self-reporting measures of cardiovascular disease, along with lack of control for important confounders, contribute to the low quality ratings for the identified studies. The magnitude of the reported effects across studies is small.

4.3.5 Is there a dose–response relationship between environmental noise and cardiovascular health?

A small number of studies formally examined whether there was a dose–response relationship between noise exposure and cardiovascular outcomes. These studies suggested such a relationship. Many studies also reported that stronger relationships with cardiovascular outcomes were observed as noise levels increased (Babisch et al., 2012, 2014a, 2014b; Bluhm et al., 2007; Chang et al., 2012; Dratva et al., 2012; Eriksson et al., 2010a; Gan et al., 2012; Hansell et al., 2013; Jarup et al., 2008; Kälsch et al., 2014; Liu et al., 2013). These differed considerably in terms of how noise exposure was quantified. For example, some examined effects per 1 dB, 5 dB, or 10 dB increases, while others examined varying categories of noise exposure.

Very limited data was available regarding threshold effects. Given the variability in research designs and low study quality, summary threshold effects could not be determined from the studies in this review. Individual studies offer findings that indicate levels at which adverse outcomes are observed. These do not indicate clear thresholds but may inform future research that examines potential thresholds. These findings are outlined below for each of the three main noise sources.

Aircraft noise

Some studies indicate that average day-evening-night noise levels are associated with adverse cardiovascular outcomes: ≥ 50 dB L_{den} (Franssen et al., 2004), > 55 dB(A) L_{den} (Correia et al., 2013; Rosenlund et al., 2001), ≥ 55 dB(A) L_{Aeq} (Eriksson et al., 2007), ≥ 60 dB(A) L_{den} (Huss et al., 2010), or > 70 dB(A) L_{den} (Matsui et al., 2001). In terms of specific periods, daytime levels above 63 dB(A) have been linked with adverse cardiovascular outcomes (Hansell et al., 2013). Focusing specifically on the period from 3am to 5am, Greiser et al. (2007) found that noise levels ≥ 40 dB(A) were linked with adverse cardiovascular health. In addition to averaged noise events, Rosenlund et al. (2001) found that maximum noise levels > 72 dB(A) were linked with poor cardiovascular health.

Road traffic noise

Several studies found a significant relationship above 55 or 60 dB(A) L_{Aeq} . (Bendokiene et al., 2011; Bluhm et al., 2007; Bodin et al., 2009; Regecova and Kelleroova, 1995); Yoshida et al. (1997) found a significant effect at noise levels ≥ 65 dB(A) L_{Aeq} . Another study found a significant relationship at noise levels ≥ 60 dB(A) L_{den} (Banerjee et al., 2014). Two others indicate higher thresholds, with effects observed at > 70 dB(A) $L_{Aeq,6-22hours}$ (Babisch et al., 2005) and ≥ 80 dB(A) L_{Aeq} (Chang et al., 2011).

Rail noise

There was insufficient evidence to draw any conclusions on the relationship between rail noise and cardiovascular health.

4.3.6 Is there any evidence that certain populations are vulnerable to the effects of environmental noise on cardiovascular health?

Aircraft noise

Two studies indicated that the association between aircraft noise exposure and hypertension was stronger in older individuals (Eriksson et al., 2007; Rosenlund et al., 2001). Eriksson et al. (2010a) found that the association of aircraft noise with hypertension was evident in males (but not females). Babisch et al. (2013) and Eriksson et al. (2010a) found the effects of aircraft noise on cardiovascular outcomes were pronounced in individuals who reported high levels of noise annoyance.

Some studies also reported that the effects of noise exposure were most pronounced in individuals who had lived in noise-exposed areas for a longer period. For instance, Huss (2010) found that the association between aircraft noise and myocardial infarction mortality was greatest in individuals who had lived in the area for 15 years or more. This is consistent with the HYENA study (also see Floud et al., 2013) where an association between aircraft noise and self-reported cardiovascular disease was evident only in those who had lived in the area for more than 20 years.

Road traffic noise

The relationships with cardiovascular outcomes were found to vary by several factors. Several studies reported stronger associations between traffic noise exposure and outcomes such as hypertension (Bluhm et al., 2007; de Kluizenaar et al., 2007), coronary heart disease (Banerjee

et al., 2014), myocardial infarction (Grazuleviciene et al., 2004) in middle-aged adults (aged 55–64 years). Sørensen et al. (2011a) found the association between road traffic noise and stroke was evident only in individuals aged over 65. Two studies indicated that the association of road traffic noise with cardiovascular outcomes was evident in individuals who had lived in an area for a longer period (Babisch et al., 2005; Barregard et al., 2009). Five studies reported significant differences by gender. The associations of road traffic noise with coronary heart disease (Banerjee et al., 2014) and hypertension (Bendokiene et al., 2011; Bjork, 2006; Lercher and Widmann, 2013) were stronger in females. In contrast, Belojevic (2008b) found that the relationship between road traffic noise and hypertension was stronger in males.

The effects of road traffic noise on cardiovascular outcomes were also stronger in individuals with higher noise sensitivity (Lercher and Widmann, 2013) and in those without hearing loss (Selander et al., 2009).

4.3.7 Does the association between environmental noise and cardiovascular health vary by noise source?

Most studies in this review examined the effects of one noise source (see de Kluizenaar et al., 2013). Although many other studies examined multiple noise sources, direct comparisons of effects were not made. Some studies investigating the effects of both road traffic and aircraft noise found significant associations for aircraft noise but not for road traffic noise. This may suggest that the effects of aircraft noise are stronger, but this is a very tentative conclusion. It is possible that aircraft, rail and road traffic noise have differential effects on cardiovascular health, but existing evidence is not conclusive.

4.3.8 Is there any evidence that annoyance is a mediator linking environmental noise exposure to cardiovascular health?

Many studies discussed annoyance as a potential pathway by which environmental noise exposure could influence cardiovascular health. However, only a few studies tried to examine whether annoyance was a mediator (see Fyhri and Klaeboe, 2009) and the evidence was inconclusive.

4.4 Conclusion

Variation in research design, study quality, adjustment for confounders, and outcome reporting make construction of dose–response relationships difficult for environmental noise and cardiovascular health.

The systematic review identified 65 studies published between 1994 and 2014 investigating the relationships between exposure to environmental noise and cardiovascular health. In general, the results were mixed, particularly for road traffic noise; the effects of rail noise on cardiovascular disease outcomes were not conclusive. Findings for the effects of aircraft noise were generally more consistent. However, it is important to note that for all noise sources, the magnitudes of the associations with cardiovascular disease were small. Small effect sizes are not surprising given that environmental noise could be one of a multitude of risk factors for cardiovascular disease. Other factors such as cigarette smoking and heredity probably play a much larger role in influencing an individual's level of risk.

It is important to note that there are some important limitations of the evidence base. These limitations include a large number of studies using self-reported measures, variation in study designs, quantification of noise exposure, site at which noise exposure was measured, and differences in the scope of confounding variables controlled. These issues mean it is not possible to identify a clear threshold where the effects on cardiovascular health emerge or worsen. As a

result, an NHMRC rating statement of C is applied to the overall body of evidence: the body of evidence has limitations and care should be taken in the interpretation of findings. See appendix A for details on ratings.

Further research is needed using designs that can demonstrate causality, using objective outcome measures. Controlling for a broad range of potential confounders is important to rule out the possibility of residual confounding. This is particularly the case for air pollution, which may be an important confounder but is not controlled in many studies. Based on existing research, vulnerable groups may include older adults. There is an absence of studies investigating annoyance as a mediator.

5 NOISE AND COGNITION

5.1 Introduction and background

Cognition is the process of learning that includes thinking, understanding and remembering. A large number of studies have examined the relationships between exposure to different sources of environmental noise – road traffic, aircraft and rail – and cognition. Associations have important implications since good cognitive performance is linked to higher quality of life, improved mental health and better academic and job performance. However, many aspects of the relationship between environmental noise and cognition remain unclear.

5.2 Systematic review of the literature

A systematic review of the literature was conducted for studies investigating the relationship between environmental noise and cognition for the period January 1994 to March 2014. This is further detailed in appendix A.

5.2.1 Search results

The flow chart below details the results of the search process.

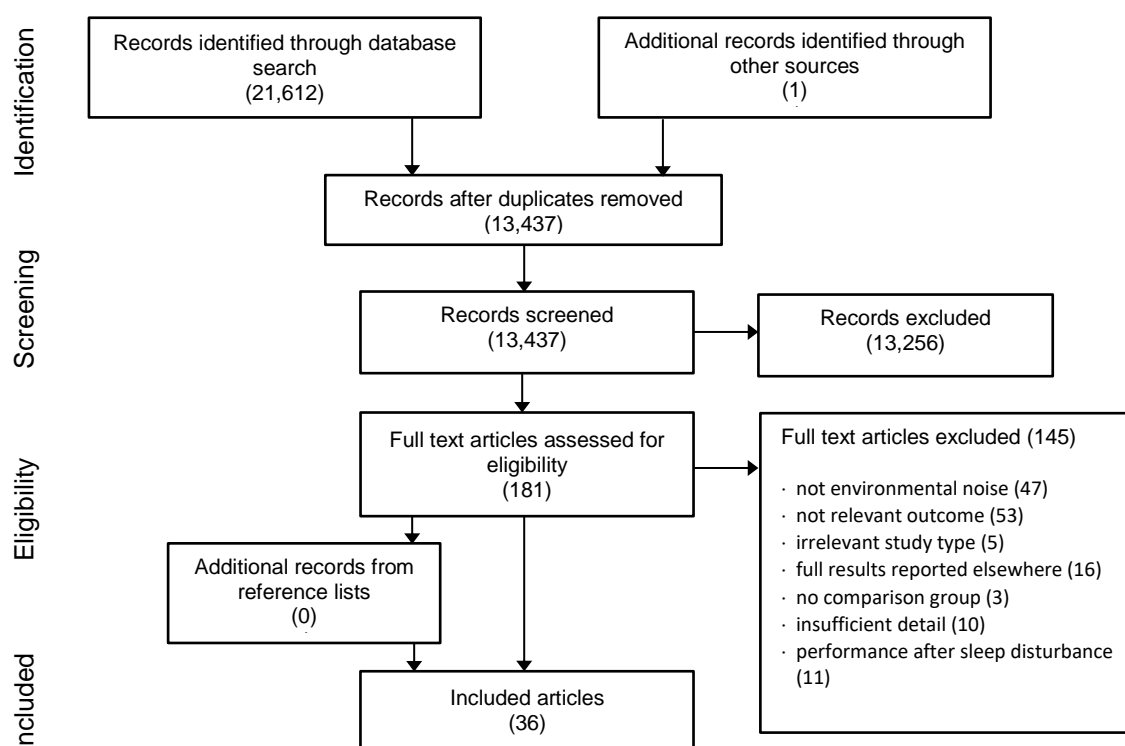


Figure 5-1: PRISMA flow chart. Number of articles identified and reviewed during the systematic review (Moher et al. 2009)

5.2.2 Overview of included studies

Study types and settings

Of the 36 articles identified, 29 were from distinct studies (some articles reported on the same data); a total of 14 observational and 15 experimental studies were included in the review. Most of the observational studies (11) were solely cross-sectional (NHMRC level IV), two included

both cross-sectional and prospective cohort (NHMRC level II) components, and one was a controlled before and after study (NHMRC level III-3).

All of the experimental studies were either non-randomised experimental studies (8) (NHMRC level III-2) or pseudo-randomised studies (7) (NHMRC level III-1). Most were based in sound and temperature controlled laboratories (12), while three were conducted in classrooms.

5.2.3 Noise exposure and how it was measured

Most of the observational studies explored aircraft noise (8 studies), followed by road traffic noise (4) and general community noise (3). Most experimental studies simulated road traffic noise (12 studies), with a small number simulating aircraft noise (3), and rail noise (1).

For observational studies, noise exposure was measured by direct measurement with sound level meters in various locations (5 studies), or estimated using models (8). One study did not clearly specify the measurement method. Experimental studies delivered noise levels in a controlled way to participants.

The most common noise measures used were A-weighted equivalent sound levels (L_{Aeq}) for various periods. Maximum sound pressure levels (L_{Amax}) were also commonly used.

All of the observational studies involved children from seven to 16 years old. Experimental studies involved university students and young adults (7 studies), primary and secondary school students (5), and only one involved adults aged from 35 to 65 years.

5.2.4 Types of outcomes reported

Most studies explored multiple outcomes. The most common outcomes explored in observational studies were reading comprehension (8 studies), memory (7) and attention (6). The most common outcomes explored in experimental studies were memory (8 studies), attention (5) and mathematical tasks (4).

Most studies used standardised or well-known tests to assess outcomes.

5.2.5 Quality ratings

GRADE is a structured process for rating quality of evidence in systematic reviews. Quality ratings according to the GRADE criteria are shown in Table 5-1. This indicates that on aggregate, the quality of the evidence was rated as low.

All included studies are listed in section 8.5. GRADE criteria are detailed in appendix A.

Table 5-1: GRADE evidence profile for environmental noise and cognition (29 studies)

No of studies (design)	Reasons for rating quality down	Reasons for rating quality up	Key findings	Quality score
Reading (skills and comprehension)				
Six (cross-sectional)	Some risk of bias	None	Aircraft noise at school has a detrimental effect on children's reading comprehension	⊕⊕○○ Low
Three (prospective cohort)	Some inconsistency	None	Detrimental effects of aircraft noise on children's reading may not persist over time, especially if noise exposure is changed	⊕⊕⊕○ Moderate

No of studies (design)	Reasons for rating quality down	Reasons for rating quality up	Key findings	Quality score
Two (experimental)	Some risk of bias Some indirectness / applicability (see GRADE guidelines)	None	Road traffic noise may affect reading speed in children but no effect was found on reading comprehension in children	⊕⊕⊕○ Moderate
Memory (short and long term)				
Six (cross-sectional)	Serious risk of bias Some inconsistency	None	Aircraft noise may affect long term memory in children. No effect of road or aircraft noise on short term memory	⊕⊕○○ Low
One (prospective cohort)	Only one small study	None	Chronic exposure may have detrimental effect on long term memory in children which is not immediately resolved by removing noise	⊕⊕○○ Low
Six (experimental)	Serious risk of bias Some indirectness	None	No effect of acute road or aircraft noise on short term memory	⊕⊕⊕○ Moderate
Attention				
Four (cross-sectional)	Some risk of bias Some inconsistency	None	Mixed results	⊕⊕○○ Low
One (prospective cohort)	Only one small study	None	No significant findings	⊕⊕○○ Low
Four (experimental)	Some risk of bias Some inconsistency Some indirectness	None	No effect of noise	⊕⊕⊕○ Moderate
Academic achievement (student, school and borough level measures)				
Five (cross-sectional)	Serious risk of bias Serious inconsistency	None	Noise at school may affect achievement (one high quality study)	⊕⊕○○ Low
Mathematics tasks (arithmetic, mathematical reasoning)				
Four (experimental)	Serious risk of bias Some indirectness	None	No effect of road traffic noise	⊕⊕⊕○ Moderate

5.3 Summary of findings from the systematic review

5.3.1 What is the evidence of the effect of environmental noise on cognition?

This systematic review identified 29 primary studies published between 1994 and 2014 examining the relationship between environmental noise exposure and cognition. Fourteen studies were observational and 15 were experimental. The main findings were mixed and are summarised below.

These studies generally measured the noise exposure, or exposed the participants, within the learning environment.

5.3.2 Observational studies

The observational studies examined the relationships between environmental noise exposure and a range of cognitive outcomes. Eight studies examined aircraft noise and four road traffic noise. A further three assessed general community noise, which included a combination of noise sources but did not allow for the sources to be distinguished from one another. Most studies were conducted on samples of children. Evidence of a relationship between environmental noise exposure and cognition was mixed across these studies.

Aircraft noise

Six of the eight studies indicated a significant relationship between aircraft noise exposure and cognitive outcomes. For example, they reported that exposure to aircraft noise was cross-sectionally associated with poorer reading comprehension (Evans et al., 1995; Evans et al., 1997; Seabi et al., 2010; Seabi et al., 2012, RANCH study and Haines et al., 2001a, b). The RANCH study and Haines (2001a, b) study found that the relationship did not maintain significance when explored through a prospective cohort study. Mixed results were found for memory and attention with four studies finding a significant relationship (Evans et al., 1995; Haines et al., 2001; Seabie et al., 2010 and the RANCH Study). The remaining two indicated aircraft noise exposure was not associated with reading comprehension, memory, attention and academic achievement (Haines et al., 2001c, 2002).

Road traffic noise

Two of the four studies provided some support for an association between road traffic noise and cognition. Belojević et al. (2012) found that higher road traffic noise was associated with poorer executive functioning in boys but not girls. The RANCH study indicated that road traffic noise was associated with impaired recognition memory, but not reading comprehension (Clark et al., 2006; Clark et al., 2012; Stansfeld et al., 2005; Stansfeld et al., 2010). Two studies conducted by Xie et al. (2010, 2011) indicated that road traffic noise was not associated with measures of academic achievement.

Generic environmental noise

Two of the three studies indicated that generic environmental noise (total noise levels measured outside schools or homes) was associated with poorer cognitive outcomes. Lercher et al. (2003) found that increased environmental noise was associated with impaired memory, while Pujol et al. (2014) found increased environmental noise was associated with poorer academic achievement. Another study conducted by Shield et al. (2008) found mixed support for a relationship between environmental noise (excluding aircraft noise) and cognitive outcomes. They found that higher levels of noise were associated with poorer academic achievement in some, but not all, schools.

Study limitations

The quality of the observational studies was generally low, reflecting a combination of factors including study design and a high risk of bias. For example, most of the studies were cross-sectional, with only two studies examining the prospective associations between environmental noise and cognition. This is a major limitation because cross-sectional studies are not able to provide insight into the direction of causation between noise and cognition. The RANCH study and Haines et al. (2001a, b) also reported cross-sectional associations between noise exposure and poorer cognition. However, these associations were not supported in the prospective analysis. This raises further concerns on the validity of the cross-sectional findings.

Most of the studies (eight out of 13) had a high risk of bias, mainly reflecting the lack of control for relevant confounding variables. This is an important consideration because significant results reported by these studies could reflect residual confounding rather than a true relationship between noise and cognition. Three of the nine studies had a moderate risk of bias, reflecting the inclusion of some confounders but omission of some key confounders such as socioeconomic status. The adjustment of confounders differed substantially between studies, particularly for measures of socioeconomic status.

Two studies, the RANCH and the Pujol et al. (2014) studies, had a low risk of bias. Several articles reported on the RANCH study, which demonstrated significant relationships between exposure to aircraft noise and poorer cognition across measures of reading comprehension, memory and attention. The RANCH study also indicated that road traffic noise was associated with some impairments in memory. Pujol et al. (2014) examined a sample of 586 children and found that general environmental noise was associated with impairments in standardised measures of academic achievement.

The observational studies examined several measures of cognition. For example, articles using data from the RANCH study used several standardised measures to assess reading comprehension and different components of memory, such as episodic and prospective memory. Studies also used generic indicators of overall executive functioning (Belojević et al., 2012) or standardised school performance scores (Haines et al., 2002; Shield et al., 2008; Pujol et al., 2014; Xie et al., 2010, 2011). Many other studies assessed domains of cognitive performance including reading, memory, attention, speech perception and intelligence (Haines et al., 2001a, c).

The variations in outcome measures may partly explain the inconsistent findings and limits the conclusions that can be drawn. Further, because most studies examine only a select range of cognitive outcomes, they do not provide a comprehensive insight into the effects of environmental noise on cognition.

The type of noise exposure indicator used is relatively consistent across the studies (usually L_{Aeq} or L_{Amax}). However, how the noise exposed was estimated – such as direct measurement or contour maps – and the site at which it was measured – building façade or participant's ear – varied considerably. This complicates a synthesis of the evidence.

5.3.3 Experimental evidence

Fifteen experimental studies examining the effects of environmental noise on cognitive outcomes were identified in this review. Twelve studies examined road traffic noise, three aircraft noise, and one rail noise, although some examined more than one noise source. The findings of these studies are summarised below.

Road traffic noise

Six of the 12 studies indicated that increased road traffic noise was associated with poorer cognitive performance. One study (Belojević et al., 2001) found that noise was not associated with cognitive performance in the total sample, although a significant effect was observed in introverts, but not extroverts. Three studies indicated that noise was not significantly associated with cognitive outcomes. Finally, two studies reported that increased noise led to improvements in cognitive performance. Alimohammadi et al. (2013) found that exposure to two hours of road traffic noise (71dB(A)) led to improved attention and concentration. However, these findings could feasibly be attributed to practice effects. White et al. (2012) reported that exposure to noise (road traffic and aircraft noise) led to faster reaction times, but this is not necessarily indicative of improved performance as accuracy was not affected by noise.

Aircraft noise

Two studies indicated that aircraft noise was not significantly associated with cognitive performance. As noted above, White et al. (2012) found that road traffic and aircraft noise were significantly associated with faster reaction times, but not differences in performance accuracy.

Rail noise

Klatte et al. (2007) found that rail noise did not lead to any differences in memory, listening comprehension, written language acquisition or visual recall.

Study limitations

The quality of the experimental evidence was moderate, with eight studies found to have a low risk of bias. But several other issues relating to the experimental evidence warranted consideration. One concerned the large variation of cognitive outcomes assessed between studies. The range of cognitive outcomes included attention, memory (short-term, long-term, prospective, cued recall), reading comprehension, speech perception, intelligence and academic performance. When similar outcomes were assessed, different approaches were used. For example, several studies examining the effects of environmental noise on reading comprehension used different measures such as the Suffolk Reading Scale (Haines et al., 2001a) and the Woodcock Reading Mastery Test (Evans et al., 1997). The variation in types of cognitive outcomes, and the measures used to assess them, limits comparisons between studies.

The nature of the experimental manipulation also differed considerably between studies. These related to the duration, mean levels and peak levels of noise exposure. There were also substantial variations in noise levels in the control or 'quiet' conditions used as a reference in these studies. These variations further limit comparisons that can be made between studies.

It is also important to note that these experimental studies assess the acute effects of noise on cognition and may lack external validity. That is, while the risk of bias was low in many studies, the results of these studies do not provide an indication of the effects of chronic noise exposure on longer term cognitive outcomes.

5.3.4 Is there a dose–response relationship between environmental noise and cognition?

None of the studies identified formally examined dose–response relationships between environmental noise and cognitive outcomes. However, some studies did report significant linear associations between noise exposure and cognition, suggesting that the effects on cognition are more pronounced at increased noise levels (Clark et al., 2006; Matheson et al., 2010).

The studies in this review did not provide a clear indication of dose–response relationships or threshold effects. An important consideration is that there may be distinct threshold effects for

different cognitive outcomes, such as memory versus attention. Further, many of these studies examined the acute effects of noise on cognition and provide only a limited insight into the effects of chronic noise exposure. Chronic exposure could have a different relationship with cognitive outcomes.

5.3.5 Is there any evidence that certain populations are vulnerable to the effects of noise on cognition?

Most of the studies were conducted in children, with only a few on adults. For the studies examining children, there was very limited evidence as to whether certain populations were more vulnerable to the effects of environmental noise on cognition. Belojević et al. (2012) found a significant detrimental effect of road traffic noise exposure at home on teacher-rated executive functioning in boys but not girls. However, few other studies in children examined sub-group effects.

Similarly, there was insufficient evidence as to whether any adult sub-populations were more vulnerable to the effects of environmental noise on cognition.

5.3.6 Does the association between environmental noise and cognition vary by noise source?

There was limited evidence as to whether the associations between environmental noise and cognition varied by noise sources. This is primarily because very few studies examined the effects of multiple sources of noise. Because studies used different methods, it was not possible to directly compare results.

Clark et al. (2006) is an example of one study that compared the effects of different noise sources. They found that aircraft noise, but not road traffic noise, was significantly associated with impaired reading comprehension. Clark et al. (2006) suggested that this may occur because aircraft noise is more intense and less predictable than road traffic noise. The transient nature of aircraft flyovers, which have short-term high noise levels, may disrupt children's concentration and distract them from learning tasks. The constant nature of road traffic noise may allow children to habituate and not be distracted.

5.3.7 Is there any evidence that annoyance is a mediator linking environmental noise exposure to cognition?

Clark et al. (2006) examined whether noise annoyance was a mediator linking noise with cognition. Their results indicated that annoyance was not a significant mediator. None of the other studies in this review formally examined the role of annoyance as a mediator of these relationships. However, many studies discussed annoyance as a potential mediator.

5.4 Conclusion

The systematic review identified 29 primary studies (14 observational and 15 experimental) from 35 papers published between January 1994 and March 2014 examining the associations between environmental noise and cognitive outcomes. There is some evidence that increased levels of environmental noise are associated with poorer cognitive performance as reflected by a range of measures assessing reading comprehension, memory and attention. However, many of the findings between studies were mixed, and the nature of the relationship between environmental noise and cognition requires further investigation.

In general, the quality of the observational evidence included in this review was low, and experimental studies were considered to have a lower risk of bias. Regardless of risk of bias, the results were generally inconclusive. From the systematic review, it is therefore not possible to

draw any meaningful conclusions on threshold effects, sub-group differences, or differential effects between noise sources. There is also insufficient evidence to draw any conclusions on the role of annoyance as a mediator. As a result, an NHMRC rating statement of D is applied to the overall body of evidence: the body of evidence is weak and findings cannot be trusted.

It is plausible that a relationship exists between environmental noise and cognitive performance. For example, environmental noise could be a source of distraction and thus interfere with task performance. Environmental noise may also induce hyper-arousal and lead to deficits in performance. It is also plausible that environmental noise has an indirect effect on cognition through disturbed sleep. Although these mechanisms are often discussed, evidence of a strong association is still lacking.

6 DISCUSSION

With future urban population growth, a significant and increasing number of people in Australia are likely to be adversely affected by exposure to environmental noise. The number exposed to potentially harmful levels of environmental noise is yet to be comprehensively quantified.

Chapters 3, 4 and 5 systematically identify and appraise the evidence on the effect of exposure to environmental noise on sleep, cardiovascular and cognitive outcomes. The systematic reviews also considered the evidence for dose–response relationships, vulnerable groups and possible thresholds for risk.

The expert advisory group considered an analysis of the highest quality studies – studies with a risk of bias rating of one or two and an NHMRC higher quality study design – was important for further interpretative guidance.

This guidance can assist regulatory authorities, public health professionals and others by:

- providing insight into the likely causal probability
- identifying if there are broad threshold boundaries for health effects
- indicating the magnitude or importance of the effects described.

The following sections provide an additional synthesis of the available evidence from higher quality studies for sleep, cardiovascular and cognitive outcomes, along with limitations in the current literature.

6.1 Discussion on higher level studies with sleep related outcomes

Outcomes and their importance

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, disturbance can also be measured through social surveys where individuals are asked to self-evaluate their sleep quality. Physiologically, sleep can be monitored using a sleep polygraph that measures total sleep time, sleep efficiency, total time in various sleep stages as well as arousals and awakenings. Motility (body movements) can be detected using accelerometers or actimetry and are also a useful indicator of sleep disturbance. A problem for interpretation in the systematic review was the proliferation of outcome measures. In general electroencephalogram awakenings are an acceptable proxy measure of sleep disturbance. However, small increases in awakenings have uncertain effects on sleep quality and uncertain long-term health consequences.

The systematic review examined a total of 79 studies, 43 of which were observational and 36 were experimental. The evidence base, while extensive, was not rated highly in terms of overall quality. An NHMRC rating statement of C was given. The low quality rating reflected issues around study design (most were cross-sectional) and a high risk of bias within studies (primarily due to measurement of sleep and control of confounders). These issues are detailed in chapter 3.

Higher quality studies

Higher quality studies included field studies with ratings of NHMRC III-2 and risk of bias one or two or NHMRC II and risk of bias one or two (Basner et al., 2006; Horne et al., 1994; Öhrström et al., 2006; and Passchier-Vermeer, 2002). They also included experimental studies (all III-1 or III-2) with a risk of bias score one, (Basner and Samel, 2005; Basner et al., 2011; Griefahan et al., 2006a; Saremi et al., 2008). See appendix A, Table A-2 for the risk rating system. These are discussed below.

The field studies by Basner et al. (2006) and Passchier-Vermeer (2002) measured the noise a participant was exposed to indoors in their home and found a significant association between noise and an impact on a sleep parameter. Outcomes included reduced rapid eye movement (REM) sleep duration, increased sleep awakenings and increased motility as measured by actimetry.

Basner et al. (2006) examined awakenings and sleep stage transitions in response to aircraft noise events in a field study of 64 subjects. Sleep outcomes were measured using polysomnography, and sound pressure levels (SPL)($L_{As,max}$) were recorded inside the bedroom at the participant's ear as well as outside at the façade. Awakening probability increased with maximum SPL of an aircraft noise event. A threshold value of 33 dB(A) was found in the study, although it was noted that the effect was small, with only 0.2 per cent probability of awakening at an aircraft noise event maximum SPL of 34 dB(A) ear. The study showed a dose–response relationship with probability of awakenings increasing as maximum SPL increased. A 10 per cent rise in awakening probability corresponded to 73.2 dB(A) ear.

The study by Passchier-Vermeer (2002) measured aircraft noise both indoors and outdoors at the participant's residence and found indoor noise measurements – but not outdoor – were significantly associated with increased motility. Studies that more precisely measured the participants' noise exposure more clearly supported the influence of environmental noise on sleep.

Horne et al. (1994) and Öhrström et al. (2006) did not use indoor noise monitoring, but for neighbourhood noise levels or modelled levels for the façade of the house they found less clear relationships. Horne et al. (1994) found that most aircraft noise events were not associated with an awakening, as measured by actimetry, and that other factors such as the presence of young children and concurrent illness, were more important. The study by Öhrström et al. (2006) found mixed results, with some sleep parameters improved in high noise areas, although they were unable to adequately control for a government noise insulation program available in the highest noise area.

The higher quality experimental studies found similar outcomes (Basner and Samel, 2005; Basner, 2011; Griefahan et al., 2006a; Saremi et al., 2008). All experimental studies used polysomnography and, owing to their experimental design, tended towards better characterised or controlled noise exposure. The results were similarly small in magnitude of effect but all found statistically significant effects of noise on sleep. This included effects on sleep awakenings, sleep onset latency, sleep structure and micro-arousals.

The magnitude of these effects was low and the impact on sleep uncertain. There was insufficient evidence to determine a dose–response curve. There was also insufficient evidence across all studies to identify a specific threshold. However, there was consistency across higher quality studies when the threshold started at 55 dB L_{Amax} façade.

Other guidance recommendations

In recent years, WHO Europe has published two reports based on extensive reviews of the literature: the WHO Night Noise Guidelines for Europe (2009) and the Burden of Disease from Environmental Noise (2011). The night noise guidelines report identified threshold levels for a series of effects (biological, sleep quality, well-being and medical conditions), for which sufficient evidence was available. It identified children, elderly people, pregnant women and shift workers as at-risk groups. This report concluded with a proposed lowest observable adverse effect level (LOAEL) night noise guideline level of 40 dB $L_{night,outside}$ (WHO, 2009). This is not consistent with the threshold levels identified in the higher level studies described above.

The burden of disease report relied on several assumptions to arrive at estimates for exposure-response relationships. These were used to estimate the disease burden from environmental noise, measured in Disability Adjusted Life Years (DALYs). Such estimates of dose-response relationships and thresholds need to be interpreted with caution.

6.2 Discussion on higher level studies with cardiovascular outcomes

Outcomes and their importance

Cardiovascular outcomes reported in the studies in the systematic review are indisputably important health effects. Outcomes reported are hypertension (56 studies), cardiovascular disease usually comprising myocardial infarction or ischaemic heart disease (14 studies), heart failure and stroke. A variety of studies, equivalent to chamber studies in air pollution research, demonstrated acute effects of noise exposure on heart rate, blood pressure, insulin and catecholamine release.

A total of 65 studies was included in the systematic review. The overall body of evidence was given an NHMRC rating statement of C, where the body of evidence has limitations and care should be taken in interpreting findings. Higher quality non-experimental studies (Babisch et al., 1999; Beelen et al., 2009; Chang, 2009; de Kluizer et al., 2013; Eriksson, 2007 and 2010; Gan et al., 2012; Sørensen et al., 2012a) included cardiovascular outcomes with a risk of bias rating of one or two and a prospective cohort design (NHMRC Level II evidence for aetiological questions).

Higher quality studies

Three higher quality studies addressed the outcome of hypertension (Eriksson, 2007 and 2010; Chang, 2009). Those by Eriksson used the Stockholm Diabetes Prevention Program Cohort to investigate the effects of modelled aircraft noise on self-reported diagnosis of hypertension. The earlier study found a significant association between increasing noise and escalated rates of self-reported hypertension. The second study by Eriksson (2010), which controlled for more confounders and had a longer follow-up period, found persistent effects only for men. Chang et al. (2009) investigated the effect of environmental noise (measured on a personal device that logged noise levels every five minutes) on blood pressure (measured every 30 to 60 minutes throughout the study period). This study found an association between increasing noise and short-term rises in blood pressure in young adults.

Five higher quality studies, all prospective cohort studies, examined cardiovascular outcomes more generally (including coronary heart disease and cerebrovascular events) as well as coronary heart disease specifically (Babisch et al., 1999; Beelen et al., 2009; de Kluizer et al., 2013; Gan et al., 2012; Sørensen, 2012). Effects seen were small and significant in only the three studies that examined cohorts of more than 50,000 people (Beelen et al., 2009; Gan, 2012; Sørensen, 2012). Sørensen et al. (2012) found a linear dose-response for traffic noise and myocardial infarction throughout the exposure range of the study (42-84 dB). As all these studies assessed exposure to road noise, consideration of air pollution as a potential confounder is important. Only two studies considered both cardiovascular risk factors and air pollution in their analysis, with the smaller cohort (Sørensen, 2012) finding a significant effect of noise, and the larger cohort (Beelen et al., 2009) finding a non-significant trend. A trend towards increased cardiovascular outcomes with noise was observed in all higher quality studies, be it statistically significant or not.

Most of the higher quality studies found an effect of noise on cardiovascular outcomes including hypertension, coronary heart disease and cerebrovascular disease. In general, effect sizes were low. Studies with fewer subjects often found non-significant trends towards an effect, while studies with more subjects found small but more often significant effects. Although the magnitude

of effect was low and the impact of these effects uncertain, it is still possible to reach limited conclusions around adverse effects on cardiovascular health.

Higher level studies suggest a general threshold for cardiovascular disease outcomes, which may be observed as low as 52 dB(A) measured at the façade (or 42 dB(A) at the ear using an assumption of 10 dB loss across the façade) but which are definitely observed as having adverse health effects starting in the range 55–60 dB(A) façade. These outcomes are for chronic exposure to road traffic noise estimated using a standard composite noise metric (usually L_{den}).

Other guidance recommendations

WHO Europe's Burden of Disease from Environmental Noise report (2011) looked at the risk of cardiovascular disease (specifically ischemic heart disease and hypertension) from increased noise levels. It notes that no myocardial risk is detected at noise levels under 60 dB(A). This report relied on several assumptions to arrive at estimates for exposure-response relationships, which in turn were used to estimate the disease burden from environmental noise, measured in Disability Adjusted Life Years (DALYs). Such estimates of thresholds need to be interpreted with caution.

6.3 Discussion on higher level studies with cognitive outcomes

Outcomes and their importance

Cognitive outcomes are not commonly considered a health outcome unless they are persistent and affect the quality of social interaction, life opportunities or activities of daily living. Many of the cognitive outcomes considered by studies covered by the systematic review could be more properly considered educational or learning outcomes. Generally, experimental studies are able to report only short term cognitive deficits arising from noise interference with cognitive tasks. They provide insight into kinds of cognitive functions that noise can interfere with and possible thresholds for this interference. However, they cannot provide direct evidence for the level at which noise may cause persistent cognitive deficit.

The systematic review identified 14 observational and 15 experimental studies. The body of evidence was given an overall NHMRC rating statement of D, where the body of evidence is weak and findings cannot be trusted.

Higher quality studies included observational studies of NHMRC study type II (prospective cohort) and risk of bias rating one or two, or NHMRC study type IV (cross-sectional) and risk of bias rating one, and experimental studies with NHMRC study type (all III-1 or III-2) (Clark, 2006, 2013; Enmarker, 2004; Hygge, 2002; Hygge, 2003a; Klatte, 2007; Ljung, 2009; Pujol, 2014; Sandrock, 2010; Sörqvist, 2010; Stansfield, 2005; Sukowski, 2007; Trimmel, 2012). These are discussed below.

Higher quality studies

A number of these studies (mostly experimental in design) examined the relationship between noise and various aspects of memory. All studies that considered the effect of road or aircraft noise on an aspect of memory found a significant relationship with at least one aspect of memory (Enmarker, 2004; Hygge, 2003a; Sörqvist, 2010; Stansfield, 2005; Hygge, 2002). Klatte (2007), the only study that assessed rail noise, found a non-significant effect of rail noise on short term memory. Enmarker (2004) and Hygge (2002) considered attention in their studies but found noise did not have a significant effect.

The four experimental studies examined a range of noise exposures and outcomes. Three of these found an effect of noise on academic performance (Ljung, 2009; Sukowski, 2007; Trimmel, 2012). The study finding no effect of noise on academic performance (Sandrock, 2010) exposed

participants to higher levels of noise in the control group compared to other studies, which might have been a factor in the non-significant result.

Observational studies that examined the effect of noise on academic performance all considered the influence of aircraft noise alone. The RANCH studies recruited students aged nine to 10 from 98 schools around airports in the Netherlands, Spain and the United Kingdom (Clark, 2006, 2012; Stansfeld, 2005). These considered outcomes related to academic performance such as school-based tests or other academic abilities, including mathematical reasoning, grammatical reasoning and reading comprehension. The RANCH studies found a significant effect on reading comprehension but not attention (Clark, 2006, 2012; Stansfeld, 2005). A study by Pujol (2014) found a significant effect of school noise on language and mathematical performance. A follow-up study by Clark (2013) of primary school children in the London arm of the RANCH study showed only non-significant decreases in reading comprehension persisting after six years.

In general, observational studies reported a large number of cognitive outcomes, did not report consistent direction of effect of cognitive outcomes, and did not report consistent effects across studies. Studies adjusted for a large range of potential confounders. However, we cannot discount a possible residual effect from socioeconomic status or other related confounders.

The high level studies suggest that noise may acutely interfere with some aspects of cognitive performance. Impairment may vary according to type of noise source, type of task and level of difficulty. There was insufficient evidence of what the long-term effects from environmental noise may be, or whether short-term effects persist over the longer term. These mixed findings may be attributable to the quality of the study designs or absence of high quality longitudinal studies but also reflect the inherently complex nature of cognitive processing.

Other guidance recommendations

In its report on the burden of disease from noise assessment, WHO (2011) proposed a hypothetical exposure–response relationship, where it is assumed that no children are affected at levels under 50 dB(A) L_{dn} , and that 100 per cent were affected at levels over 95 dB(A) L_{dn} . However, this report relied on several assumptions to estimate exposure–response relationships that were then used to estimate the disease burden from environmental noise, measured in Disability Adjusted Life Years (DALYs). Such estimates of dose–response relationships and thresholds need to be interpreted with caution.

6.4 Limitations

Limitations imposed by the quality of the body of evidence available for the systematic reviews have been discussed in chapters 3 to 5. Many studies did not consider the duration of exposure to noise, particularly for cardiovascular disease, which could have an impact on findings. Most studies were observational studies with a high risk of bias due to potential confounding, and there are issues with external validity of experimental studies (applicability of experimental findings to real world situations). These and the heterogeneity of measurement of both noise and outcomes restricted any attempt at meta-analysis of results in the systematic reviews.

Causality is difficult to demonstrate without randomised controlled trials or prospective cohort studies, and these studies are difficult or impossible to conduct in the area of environmental noise. Sections 10 and 11 in appendix A detail the overall quality assessment process using the GRADE guidelines (Guyatt et al., 2011), informed by relevant recommendations from the NHMRC (1999).

GRADE is an accepted method of providing a structured process for rating the quality of evidence in systematic reviews. However, it was developed primarily in the context of clinical trials, and there are ongoing debates about its application for public health. This includes

environmental noise health effects, where randomised control trials are often not possible. The limitations in applying GRADE guidelines to public health evidence have been noted previously, including in a study by two members of the GRADE working group (Rehfuess and Akl, 2013). One issue identified was the low quality evidence grading for all observational studies – non-epidemiological evidence, such as experimental studies, is regarded as very low quality. Other issues included uncertainty about how to apply the GRADE criteria to narrative summaries, and potential for policymakers to misinterpret the GRADE terminology to describe the quality of evidence. The authors suggested the GRADE working group consider modifications to the criteria to better suit reviews of public health interventions.

The GRADE criteria used to rate evidence in the systematic reviews cited here have been modified to account for issues with experimental studies (see appendix A, section 7). While the formal GRADE requirement rates all observational studies as 'low quality', the studies we reviewed may have adopted close to the best feasible design for many of the measured noise outcomes.

7 SUMMARY AND RECOMMENDATIONS

This chapter summarises the findings, identifies the gaps in the literature and considers future priorities to protect and promote human health in relation to environmental noise.

7.1 Summary statement on environmental noise and sleep disturbance

There is consistency across higher quality studies to suggest a causal relationship between environmental noise and sleep disturbance above 55 dB(A) ($L_{\text{night, outside}}$) at the building façade.

Table 7-1 summarises the findings from the systematic review and areas of concern.

Table 7-1: Summary of current evidence on the effect of noise on sleep disturbance and dose-response, sources, thresholds and individual vulnerability

Concern	Summary of effects on sleep disturbance
Dose-response	It is likely there is a dose-response relationship between noise and physiological effects on sleep which some studies show begins above 32 dB(A) L_{Amax} measured at the ear (about equivalent to 42 dB(A) L_{Amax} at the façade). While physiological effects have been observed at these levels, this does not suggest this is the threshold for adverse health effects.
Variations by source	The systematic review concludes it is plausible that aircraft, rail and road traffic noise have differential effects on sleep quality. However, because available data are limited, it is not possible to draw definitive conclusions on the nature and magnitude of these differences.
Threshold	There is consistency across higher quality studies to suggest sleep disturbance above 55 dB(A) ($L_{\text{night, outside}}$) at the façade. Some studies show physiological effects below 55 dB(A) ($L_{\text{night, outside}}$) but because of the studies' limitations, the evidence was not sufficient to say when these outcomes constitute an adverse health effect.
Vulnerable populations	Evidence from the systematic review raises the possibility that some effects may be greater in certain populations, but it is not strong or complete enough to draw strong conclusions on vulnerable groups. WHO's night noise guidelines for Europe report identifies children, elderly people, pregnant women and shift workers as potential at-risk groups.
Gaps and research needs	Observational research should ideally be longitudinal in design. Use of standardised sleep measures and accurate noise exposure measures (not proxies), and appropriate control of covariates with potential to confound the findings, would help to compare and pool studies. Studies are needed that allow for further comparison of the effects of different noise sources, as well as formal examination of mechanisms that may link environmental noise and sleep (annoyance).

7.2 Summary statement on environmental noise and cardiovascular disease

The larger prospective cohort studies that more comprehensively controlled for confounders suggested a causal relationship between chronic exposure to environmental noise and cardiovascular outcomes above 60 dB $L_{\text{Aeq, day, 16h}}$ at the façade. Note that the $L_{\text{Aeq, day, 16h}}$ metric measures sound from 7 am to 11 pm and is an outdoor value.

Table 7-2 summarises the findings from the systematic review and areas of concern.

Table 7-2: Summary of current evidence on the effects of noise on cardiovascular disease and dose–response, sources, thresholds and individual vulnerability

Concern	Summary regarding effects on cardiovascular health
Dose–response	Variation in research design, study quality, adjustment for confounders, and outcome reporting make construction of dose–response relationships difficult. A small number of studies formally examined whether there was a dose–response relationship between noise exposure and cardiovascular outcomes. These studies were suggestive but not conclusive of a dose–response relationship. Many studies reported that stronger relationships with cardiovascular outcomes were observed as noise levels increased.
Variations by source	The systematic review concludes it is plausible that aircraft, rail and road traffic noise have differential effects on cardiovascular health, but existing evidence is not conclusive.
Threshold	The larger studies that more comprehensively controlled for confounders suggested adverse effect on the cardiovascular system occur above 60 dB $L_{Aeq,day,16h}$ at the façade. Note that the $L_{Aeq,day,16h}$ metric measures sound from 7 am to 11 pm and is an outdoor value. Given the variability in research designs and study quality, summary threshold effects could not be determined from the studies. Some studies offer findings that indicate levels at which adverse outcomes are observed, although these do not indicate clear thresholds.
Vulnerable populations	Evidence from the systematic review suggests the association between aircraft noise exposure and hypertension was stronger in older individuals, in those with high levels of annoyance and in individuals who had lived in noise exposed areas for a longer period. Road traffic noise was found in some studies to be associated with hypertension, coronary heart disease and myocardial infarction in middle aged adults and also in individuals who had lived in noise exposed areas for a longer time. There were significant but inconsistent gender differences in some studies.
Gaps and research needs	There is a need to better identify vulnerable groups and subgroups, and those who have lived in a high noise exposure area for a longer period (>10 years). Future studies should investigate whether factors such as annoyance mediate the association between noise exposure and cardiovascular health. Any further research should use study designs that show causality and use objective outcome measures to reduce bias. Many of the studies that considered cardiovascular outcomes did not comprehensively control for confounding, particularly air pollution.

7.3 Summary statement on environmental noise and cognition

There is some evidence that increased levels of environmental noise are associated with poorer cognitive performance. This is reflected in a range of measures assessing reading comprehension, memory and attention.

Many of the findings between studies were mixed, and the nature of the relationship between environmental noise and cognition requires further investigation.

There is insufficient evidence of a causal effect of environmental noise on persistent cognitive or learning deficits.

Table 7-3 below summarises the findings from the review and areas of concern.

Table 7-3: Summary of evidence on the effects of noise on cognition and dose–response, sources, thresholds and individual vulnerability

Concern	Summary regarding effects on cognition
Dose–response	The systematic review did not identify studies that formally examined dose–response relationships between environmental noise and cognitive outcomes. Some studies did report significant linear associations between noise exposure and cognition, suggesting that the effects on cognition are more pronounced at increased noise levels.
Variations by source	The systematic review noted there is limited evidence as to whether the associations between environmental noise and cognition varied by noise sources. This is primarily because very few studies examined the effects of multiple sources of noise. Because studies used different methods, it was not possible to directly compare results between studies. However, it is possible that aircraft noise is more disruptive to children’s concentration.
Threshold	The systematic review did not provide a clear indication of a threshold but it suggested there may be distinct threshold effects for different cognitive outcomes.
Vulnerable populations	Evidence from the systematic review is not sufficient to identify vulnerable groups. Most studies were conducted on children, and it seems reasonable to suggest that children are a vulnerable population with regards to noise and cognition. Subgroup effects among different children groups, such as gender, are inconclusive.
Gaps and research needs	More research is needed to clarify the nature of the relationship between environmental noise and cognition, taking account of specific cognitive outcomes and chronic noise exposure. These should include well-designed prospective studies and experimental studies that involve randomisation and that compare the effects of different noise sources. Observational studies would also be useful to identify vulnerable populations, which could then be further examined in experimental studies. It would be valuable for studies to examine the role of annoyance as a mediator linking environmental noise to cognition.

7.4 Overall summary statement for the effect of environmental noise on health

There is sufficient evidence of a causal relationship between environmental noise and both sleep disturbance and cardiovascular disease, to warrant health based limits for residential uses.

During the night-time, an evidence based limit of 55 dB(A) at the facade using the $L_{eq,night}$, or similar metric and an eight-hour night-time period is suggested.

During the day-time, an evidence based limit of 60 dB(A) at the facade measured using the $L_{eq,day}$, or similar metric and a 16-hour day-time period is suggested.

7.5 Recommendations

It is likely that community and public health concern over environmental noise will grow. This is particularly due to increasing urban density along busy transport corridors, growth in urban transportation, significant shifts in inner city land use, growing residential use of rezoned industrial areas, and greater information and evidence.

This report confirms and expands on the findings of the enHealth report on the health effects of environmental noise published in 2004. The current evidence indicates that environmental noise is an ongoing public health problem, and one that deserves more attention than it receives.

Four main recommendations are presented as measures to address the health impacts of environmental noise. They are:

1. recognise that environmental noise is a health risk
2. promote measures to reduce environmental noise and health impacts
3. address environmental noise in planning and development activities
4. foster research to assist policymaking and action.

These recommendations are not considered exhaustive and may be subject to change in light of further evidence.

7.5.1 Recommendation 1: Recognise that environmental noise is a health risk Policy

Recommended actions	Responsibility	Priority
Consider this review when developing national environmental noise goals	State and territory health agencies	High
State and territory and Australian Government agencies to include noise as an important environmental health issue for strategic and local planning	State and territory health agencies	High
Review adequacy of existing health guidelines in state and territory legislation	enHealth	High

Interventions

Recommended actions	Responsibility	Priority
Promote awareness of the impacts of environmental noise on health	Relevant agencies, stakeholders and non-government organisations	Medium

Information

Recommended actions	Responsibility	Priority
Inform communities and stakeholders of national and international standards and guidelines	State and territory health agencies, other relevant agencies, stakeholders and non-government organisations	Medium

7.5.2 Recommendation 2: Promote measures to reduce environmental noise and associated health impacts

Policy

Recommended actions	Responsibility	Priority
Review consistency of existing legislation across all levels of government	enHealth, state health, environment and planning authorities including the Australian Building and Construction Commission	High

Interventions

Recommended actions	Responsibility	Priority
Review noise arising from transportation, including noise criteria for areas adjacent to transport infrastructure	State health, environment and planning authorities including the Australian Building and Construction Commission	Medium
Promote noise mitigation measures (for example, acoustic barriers or noise insulation in residential buildings) and the use of licensing controls to limit noise impacts	State health, environment, transport and planning authorities including the Australian Building and Construction Commission	Medium

Information

Recommended actions	Responsibility	Priority
Develop a national environmental noise reduction education program, which could be supplemented with additional state-specific campaigns	enHealth, state and territory health agencies	Medium

7.5.3 Recommendation 3: Address environmental noise in planning and development activities

Policy

Recommended actions	Responsibility	Priority
Include environmental noise in the health impact assessment of proposed developments, where warranted	State health, environment and planning authorities including the Australian Building and Construction Commission	High
Determine baseline environmental noise levels to inform planning actions (noise mapping)	State health, environment, transport and planning authorities	High
Review noise control practices and how to further integrate noise control into planning processes, for all levels of government (with attention to future noise research findings)	State health, environment and planning authorities	Medium
Foster national consistency for: <ul style="list-style-type: none"> guidelines on how to minimise or prevent environmental noise arising from developments (that is, appropriate attention to layout, design and construction) limiting noise arising from major sources methods to set noise limits 	State health, environment and planning authorities including the Australian Building and Construction Commission	Medium

Interventions

Recommended actions	Responsibility	Priority
Carry out baseline monitoring of environmental noise levels over time to ascertain existing ambient levels across a broad range of populations and land use areas. This could be used to inform land use planning or burden of disease studies	Environment, transport and health agencies	High
Apply appropriate controls where noise is known to have an effect	Regulatory authorities	High
Develop national and state action plans for both the long and short term to integrate planning and research at all levels of government	enHealth, State health, transport, environment and planning authorities	Medium
Develop guidelines for noise sensitive developments for layout, design and construction	Planning, environment and health agencies	Medium

Information

Recommended actions	Responsibility	Priority
Develop state information strategies to keep communities informed of advances in measures to improve noise	State health, environment and planning authorities including the Australian Building and Construction Commission	Medium

7.5.4 Recommendation 4: Foster research to support policymaking and action Policy

Recommended actions	Responsibility	Priority
Identify factors giving rise to sensitivity to noise and vulnerability to non-auditory health effects to inform environmental, planning and health policies	State and territory health agencies, enHealth, key researchers	High

Interventions

Recommended actions	Responsibility	Priority
Conduct a rigorous evaluation of national, state and city population exposures to each major noise source	State and territory environment agencies, health agencies, such as National Health and Medical Research Council enHealth, key researchers	High
Support noise mapping projects to determine community noise exposures to each major noise source, which could be used to inform land use planning or burden of disease studies	Health, environment and transport stakeholders	High
Conduct evaluations of noise reduction schemes on community health	State health, environment and planning authorities including the Australian Building and Construction Commission, enHealth, key researchers	Medium
Promote further research on the effects of noise on learning performance in children, sleep disturbance, annoyance and cardiovascular health and mental wellbeing to establish threshold levels	State health, environment and planning authorities including the Australian Building and Construction Commission, enHealth, key researchers	Medium

Information

Recommended actions	Responsibility	Priority
Translate research findings into useful information for community and relevant stakeholders	State health, environment and planning authorities including the Australian Building and Construction Commission, enHealth, key researchers	Medium

Concluding remarks

Although the body of evidence is largely still emerging, there is sufficient evidence to suggest that noise affects health. It is important to consider actions to reduce environmental noise exposure where feasible. This would likely have a positive impact through health benefits.

A number of areas require further investigation and particularly for the Australian context. Environmental noise in rural areas has not been well researched because the low population density makes it difficult to conduct studies with sufficient statistical power to confirm or refute any hypothesis.

Lack of noise mapping and determination of population exposure by noise levels constrains estimates of the burden of disease from noise exposure. Environmental noise therefore needs to be prioritised on the research agenda.

Research that would have a direct impact on policy would be intervention studies examining the effects of change in noise exposure on changes in population health. Health agencies have a critical role to play in developing an appropriate research framework with academic institutions, transport, environment and planning agencies.

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8.6 Chapter 6

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APPENDIX A: REVIEW OBJECTIVES AND METHODOLOGY

1. Evidence reviews

NSW Health convened an expert advisory group to assist in developing this document. It also commissioned the Centre for Health Initiatives at the University of Wollongong to do systematic reviews of the evidence for three health outcomes: sleep disturbance, cardiovascular diseases and cognition.

2. Review objectives

The review identified and appraised international evidence on the influence of exposure to environmental noise on sleep, cardiovascular and cognitive outcomes.

The primary research question was: 'What is the evidence for an effect of environmental noise on sleep, cardiovascular and cognitive outcomes?'

Four sub-questions were:

1. Is there a dose–response relationship between environmental noise and sleep, cardiovascular and cognitive outcomes?
2. Is there any evidence that certain populations, such as children, are particularly vulnerable to the effects of environmental noise on sleep, cardiovascular and cognitive outcomes?
3. Does the association between environmental noise and sleep, cardiovascular or cognitive outcomes vary by noise source, such as rail, road and aircraft?
4. Is there any evidence that annoyance is a mediator linking environmental noise exposure to sleep, cardiovascular and cognitive outcomes?

A protocol was developed with guidance from the expert advisory group for this review. This outlined the scope, research questions and criteria for selecting and appraising studies, templates for extracting data, and methods for synthesising the results.

The review followed established guidelines, such as the NHMRC guidelines (1999) and the Cochrane Collaboration guidelines (Higgins and Green, 2011).

It involved six steps:

1. Refining the research question and scope
2. Conducting an extensive search of the academic literature
3. Searching the websites of international agencies and conducting Google searches to identify grey literature
4. Extracting the relevant data
5. Assessing the quality of the selected studies
6. Systematically synthesising the selected studies.

This review informs chapters 3 to 7 of this document.

3. Literature search

A comprehensive and systematic search identified all relevant studies in peer reviewed and grey literature sources published from January 1994 to March 2014. This updates the previous enHealth review published in 2004, which was not a systematic review.

An initial 'scoping search' in December 2013 provided a brief overview of the evidence base and serve as a basis for scoping decisions. The formal search was done in March to June 2014 (bibliographic database searches) and July 2014 (internet searches). The results of the database searches and citations of relevant reports and articles identified in the grey literature search were uploaded to an EndNote library (EndNote X7, www.endnote.com) for appraisal. Full details of the search process are in the chapters addressing sleep, cardiovascular and cognitive outcomes.

4. Grey literature and hand searching

Primary studies published in the grey literature (not in peer reviewed journals) were identified by searching various online sources. Websites of key organisations (identified by the expert advisory group) and Google advanced search were searched. Full details of the search methods and results of the grey literature search are in the chapters addressing sleep, cardiovascular and cognitive outcomes.

Key journals, where a large proportion of included studies were published, were also hand searched by accessing the journal online and browsing archives for the period January 1994 to March 2014. These included:

- Noise and Health
- Journal of Sound and Vibration
- Journal of the Acoustical Society of America
- Applied Acoustics.

The reference lists of included studies and other relevant reviews were scanned for any additional studies.

5. Study selection and appraisal

Studies were selected for inclusion using a two-stage process conducted by two research team members (with 20 per cent random overlap to ensure consistency). The first stage involved scanning titles and abstracts in EndNote and excluding based on obvious deviations from the inclusion criteria. Full texts were retrieved for all remaining citations. The second stage involved reading the full text to ascertain whether the study fully met the inclusion criteria. The culmination of stage two was a final dataset of included studies.

The criteria used to select studies for review are in Table A-1.

Table A-1: Inclusion criteria for the systematic reviews.

Topic	Details
Participants	The review considered all studies that involve human subjects of any age.
Time periods	The review was limited to articles published between January 1994 and March 2014. This time frame was chosen to include the most relevant and recent studies, including those reviewed for the previous enHealth noise and health guidelines (2004).
Language	English language articles were included.
Noise exposure (source and how it was measured)	<p>Studies were included if they specifically addressed environmental sources of noise. While this primarily means noise emitted from road, rail and air traffic, other sources considered relevant for this review included industrial and capital works, ventilation noise emitted from external sources in neighbouring buildings, and general community noise (not emitted from one's own property).</p> <p>Noise sources not within scope included:</p> <ul style="list-style-type: none"> Occupational noise experienced by employees in the workplace Domestic sources of noise and their effects (e.g. noise from within neighbouring apartments) Infra-sound and wind farms. <p>A number of studies looked at classroom acoustics and cognition. Most of these were excluded because the noise source of interest was either within the classroom or emitted from within the school grounds. Studies were included only if the noise source of interest was external to the school and a sufficient measure of exposure was utilised.</p> <p>Studies were also required to include a reliable measure of exposure. This included a broad array of tools from direct measurement to estimates obtained from models or contour maps. Studies were excluded if only proxy measures of noise exposure were used (e.g. noise annoyance, proximity to a roadway).</p>
Sleep outcomes	Studies were included if they addressed one or more sleep disturbance outcomes. These ranged from self-reported sleep quality to polysomnography. Studies assessing sleep disturbance among shift workers, who may not sleep during night time hours, were also included.
Cardiovascular disease outcomes	<p>The specific focus of this review was on outcomes directly relevant to cardiovascular disease; including hypertension, heart disease, stroke and diabetes.</p> <p>Many studies examined blood pressure on a continuum – participants were not categorised into blood pressure categories. These studies were included as they encompass individuals with high blood pressure.</p> <p>Studies that focused solely on changes in hormone levels (such as catecholamines) or stress responses were excluded. These outcomes are related to cardiovascular health, but they do not provide a direct insight into the effects of environmental noise on cardiovascular disease risk. Rather, these measures are likely to be part of the causal pathway linking environmental noise with cardiovascular disease.</p> <p>In addition, there are numerous studies examining the effects of environmental noise on cardiovascular activity during sleep, such as cardiac arousals. These studies were excluded from the review as they are unlikely to provide an indication of risk.</p>

Topic	Details
Cognition outcomes	<p>Cognition may be defined in a number of ways but the relevant outcomes included in this review were those that were indicators of the cognitive functioning of healthy children, adolescents and adults with normal hearing. These include such functions as memory, comprehension, logical processing, attention and vigilance. Speech perception and the way people hear sounds was the focus of a number of studies, but not deemed relevant for this review as it is more of a mediating factor in the association between noise and cognition, rather than a cognitive outcome in itself. Listening and reading comprehension were considered to be cognitive functions and were included.</p> <p>A number of studies used simulated noise delivered while participants slept in a laboratory setting to study the association between noise-disturbed sleep and cognitive performance the next day. These were deemed to be more focused on the effect of the sleep disturbance on cognition rather than noise exposure itself and were therefore excluded.</p>
Study and publication types	<p>A broad range of study types was included. Studies were excluded if they had: no control or comparison group (e.g. descriptive study); intervention studies, except where relevant cross-sectional data (baseline) was available; and animal studies.</p> <p>Peer reviewed articles, official reports, and conference papers were included. Conference abstracts were included only when sufficient information was available to extract necessary data and appraise for risk of bias. Correspondence, editorials and reviews were excluded.</p>

6. Quality assessment

The overall quality assessment process followed GRADE guidelines (Guyatt et al., 2011), informed by relevant recommendations from NHMRC (1999).

GRADE is a structured process for rating quality of evidence in systematic reviews. This process provides a summary of the evidence – the quality rating for each outcome and the estimate of effect, reflecting the extent we can be confident the estimates of effect are correct.

A range of domains were used to appraise the quality of the evidence. Risk of bias is first assessed at the individual study level. The rest are assessed by looking at the entire body of evidence for that outcome. These domains are:

1. Risk of bias – assessed at individual study level. Used to assess limitations with the study and degree of confidence in the findings
2. Inconsistency of results – inconsistency in participants, methodology and outcomes across the body of evidence. An evaluation of the similarity of point estimates and/or extent of overlap of confidence intervals may be used
3. Indirectness of evidence – the differences between study characteristics (such as participants, exposures and outcomes) and those of interest (such as populations of interest) within the body of evidence. The greater the difference, the more indirect the evidence. May be appropriate to use interchangeably with the terms ‘applicability’ and ‘generalisability’
4. Imprecision – an assessment of 95 per cent confidence intervals (CI) to ascertain whether the estimate of effect for the body of evidence is sufficiently precise. This is more difficult if CIs are not reported and is generally only used in meta-analysis
5. Publication bias – suspected when evidence comes from a number of small studies, most of which have been commercially funded

6. Large magnitude of effect – presence may justify increasing the rating for the quality of the body of evidence
7. Plausible confounding, which would reduce a demonstrated effect
8. Dose–response gradient – presence may justify rating up the quality of the body of evidence.

Quality assessment involved two main stages.

First, the risk of bias within each individual study and each individual outcome within the study was assessed. The NHMRC level of evidence for study type was also recorded.

Second, the overall quality of the body of evidence for each individual outcome was assessed. See ‘Evidence quality’ below.

7. Risk of bias

Risk of bias is the risk that authors will overestimate or underestimate the true effect of a particular exposure (Higgins et al., 2011). Risk of bias is assessed by looking at features of the design and execution of individual studies that have the potential to affect the validity of findings. Risk of bias is distinguished from the ‘methodological quality’ of a study. The latter may refer only to the extent to which study authors conducted their research to the highest possible standards and not the extent to which results should be believed. A study may be performed to the highest possible standards and yet still have an important risk of bias (Higgins et al., 2011).

Risk of bias assessment was conducted by two researchers, with inter-coder reliability checked on 20 per cent of the sample to ensure consistency, and taking into account that judgements will involve a certain level of subjectivity. Any discrepancies were reviewed by a third researcher.

Assessment of risk of bias was informed by the GRADE guidelines risk of bias criteria (Guyatt et al., 2011); and the Cochrane Collaboration risk of bias tool (Higgins and Green, 2011). Further information on the GRADE criteria is available in sections 10 and 11 of this appendix.

Quality assessment tools such as GRADE are typically developed for the assessment of randomised controlled trials. Where appropriate, GRADE guidelines were modified to be suitable for assessing the studies in this review. This applied particularly to experimental studies, as GRADE guidelines emphasise allocation concealment and blinding in the risk of bias assessment. These criteria may be less relevant to experimental studies that are not randomised control trials. Therefore, we modified GRADE criteria to include a rating of ‘randomisation and counterbalancing of allocation’. Studies using an appropriate method of allocation to experimental conditions (such as randomisation or counterbalancing) are rated as having a low risk of bias.

8. Evidence rating

Once risk of bias ratings were completed for all papers for a given outcome, a rating of the overall body of evidence was done. GRADE offers four levels of evidence quality: high, moderate, low and very low. These levels imply a gradient of confidence in estimates of treatment effect, and thus a gradient in the consequent strength of inference. Randomised trials begin as high quality evidence and observational studies as low quality evidence. Quality may be downgraded as a result of limitations in study design or implementation, imprecision of estimates (wide confidence intervals), variability in results, indirectness of evidence, or publication bias. Quality may be upgraded because of a very large magnitude of effect, a dose–response

gradient, and if all plausible biases would reduce an apparent treatment effect (appendix A, sections 10 and 11).

To be consistent with the NHMRC, we also appraised the evidence according to NHMRC levels of evidence ratings (Table A-7). These ratings were informed by GRADE ratings as well as study design. Details for interpreting each rating are shown in Table A-2.

Table A-2: NHMRC evidence statements

Evidence rating	Description
A	Findings from the body of evidence can be trusted
B	Findings from the body of evidence can be trusted in most situations
C	The body of evidence has limitations and care should be taken in the interpretation of findings
D	The body of evidence is weak and findings cannot be trusted

9. Data synthesis

Narrative synthesis is a textual approach to synthesis to ‘tell the story’ of the findings. This was chosen as the most appropriate approach to synthesis, given the diverse range of study types and the nature of the research questions.

Formal guidelines for narrative synthesis are not available. However, current guidelines for the conduct of systematic reviews (CRD, 2009) suggest that synthesis should incorporate these elements:

- developing a theory of how the intervention works, why and for whom
- developing a preliminary synthesis of findings of included studies
- exploring relationships within and between studies
- assessing the robustness of the synthesis.

These features are primarily concerned with systematic reviews of intervention studies. Only the last three elements were therefore used to guide the data synthesis stage.

10. GRADE criteria

The GRADE criteria are different for observational and experimental studies (Table A-3). Criteria 1 for experimental trials have been modified to better suit the types of studies in this review (not randomised controlled trials).

Table A-3: GRADE risk of bias criteria

Criteria	Questions
Risk of bias in experimental trials	
1. Lack of allocation concealment (changed in this review to randomisation/ counterbalancing of allocation)	Was there an adequate method of allocation? (randomisation or counterbalancing)
2. Lack of blinding	Were participants, personnel and outcome assessors ‘blind’ to intervention?

Criteria	Questions
3. Incomplete accounting of patients and outcome events	Was the trial stopped early? Were patients analysed in the groups to which they were randomised?
4. Selective outcome reporting bias	Is there incomplete or absent reporting of some outcomes and not others on the basis of the results?
5. Other limitations	Were there any other limitations that could affect the validity of the findings?
Risk of bias in observational studies	
1. Failure to develop and apply appropriate eligibility criteria (inclusion of control population)	<p>Cohort Was the cohort representative of the population of interest? Were participants in different exposure groups recruited from the same population or matched and over the same period?</p> <p>Case control Were cases and controls recruited from the same population or matched and over the same period?</p>
2. Flawed measurement of both exposure and outcome	<p>All Was the exposure clearly defined and accurately measured? Were the main outcome measures used accurate (valid and reliable)? Did they use subjective or objective measurements? Were the measurement methods similar in different groups? Were the statistical tests used to assess the main outcomes appropriate?</p> <p>Cohort Do the analyses adjust for different lengths of follow-up?</p> <p>Case control Period between the intervention and outcome the same for cases and controls?</p>
3. Failure to adequately control confounding	<p>All Were all relevant prognostic factors measured? What was missed? (genetic, environmental, socio-economic) All relevant confounders addressed in design and/or analysis?</p>
4. Incomplete follow-up	<p>All Was follow-up complete enough? Was follow-up long enough?</p> <p>Cohort Anything special about people leaving or entering the cohort?</p> <p>Cross-sectional NA</p>

Each study (or outcome, where multiple outcomes were assessed in one study) was given a score of 1, 2 or 3 based on the risk of bias found (see Table A-4 for details of scoring). At this stage the scores were not comparable across study types given that a randomised controlled trial may receive a high risk of bias score and a cross-sectional study may receive a low risk of bias score.

Table A-4: Risk of bias summary scores

Bias Score	Definition
1	Low risk of bias for all key criteria
2	Crucial limitations for one criterion or some limitations for multiple criteria sufficient to lower one's confidence in the estimate of effect
3	Crucial limitation for one or more criteria sufficient to substantially lower one's confidence in the estimate of effect

Both GRADE guidelines and the Cochrane Collaboration recommend against the use of scales yielding a score because calculating a score inevitably involves assigning weights to particular domains, which is not always justifiable (Higgins, Altman et al., 2011). However, summarising risk of bias within individual studies is useful when grading the quality of evidence across studies, which occurs at the data synthesis stage.

11. GRADE levels of evidence

Table A-5: Quality assessment criteria (Guyatt, Oxman et al., 2011)

Study design	Quality of evidence	Lower if	Higher if
Randomised trial	High	Risk of bias -1 Serious -2 Very serious	Large effect +1 Large +2 Very large
	Moderate	Inconsistency -1 Serious -2 Very serious	Dose response +1 Evidence of a gradient
Observational study	Low	Indirectness -1 Serious -2 Very serious	All plausible confounding +1 Would reduce a demonstrated effect or
	Very low	Imprecision -1 Serious -2 Very serious	+1 Would suggest a spurious effect when results show no effect
		Publication bias -1 Likely -2 Very likely	

Table A-6: Quality of evidence grades

Grade	Definition
High	We are very confident that the true effect lies close to that of the estimate of the effect
Moderate	We are moderately confident in the effect estimate: the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different
Low	Our confidence in the effect estimate is limited: the true effect may be substantially different from the estimate of the effect
Very low	We have very little confidence in the effect estimate: the true effect is likely to be substantially different from the estimate of effect

Table A-7: NHMRC evidence hierarchy (NHMRC 2009)

Level	Intervention	Diagnostic accuracy	Prognosis	Aetiology	Screening intervention
I	A systematic review of level II studies	A systematic review of level II studies	A systematic review of level II studies	A systematic review of level II studies	A systematic review of level II studies
II	A randomised controlled trial	A study of test accuracy with: an independent, blinded comparison with a valid reference standard, among consecutive persons with a defined clinical presentation	A prospective cohort study	A prospective cohort study	A randomised controlled trial
III-1	A pseudo randomised controlled trial (alternate allocation or some other method)	A study of test accuracy with: an independent, blinded comparison with a valid reference standard, among non-consecutive persons with a defined clinical presentation	All or none	All or none	A pseudo randomised controlled trial (alternate allocation or some other method)
III-2	A comparative study with concurrent controls: Non-randomised experimental trial Cohort study Case-control study Interrupted time series with a control group	A comparison with reference standard that does not meet the criteria required for Level II and III-1 evidence	Analysis of prognostic factors among persons in a single-arm of a randomised controlled trial	A retrospective cohort study	A comparative study with concurrent controls: Non-randomised experimental trial Cohort study Case-control study

Level	Intervention	Diagnostic accuracy	Prognosis	Aetiology	Screening intervention
III-3	A comparative study without concurrent controls: Historical control study Two or more single-study Interrupted times series without a parallel control group	Diagnostic case-control study	A retrospective cohort study	A case-control study	A comparative study without concurrent controls: Historical control study Two or more single-arm study
IV	Case series with either post-test or pre-test/post-test outcomes	Study of diagnostic yield (no reference standard)	Case series, or cohort study of persons at different stages of disease	A cross-sectional study or case series	Case series

12. References

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