State of the evidence for aviation noise effects on health and wellbeing

By Professor Charlotte Clark

January 2026

Version 1.0

Table of Contents

Abbreviations

AMI	Acute Myocardial Infarction
ADHD	Attention Deficit Hyperactivity Disorder
AF	Atrial Fibrillation
ANNE	Aviation Night Noise Effects
CHD	Coronary Heart Disease
CI	Confidence Interval
dB	Decibel level
dBA	Decibel level (A-weighted)
ECG	Electrocardiography
EEG	Electroencephalography
ENG	Environmental Noise Guidelines
EEA	European Environment Agency
ERF	Exposure Response Function
FAA	Federal Aviation Authority
GDG	Guideline Development Group
GRADE	Grading of Recommendations Assessment, Development and Evaluation
HA	"Highly annoyed", as defined by ISO/TS15666
HSD	Highly Sleep Disturbed
HPA	hypothalamic-pituitary-adrenal axis
ICAO	International Civil Aviation Organization
ICBEN	International Commission for the Biological Effects of Noise
ISO	International Organization for Standardization
IHD	Ischaemic Heart Disease
L_{Aeq}	Average sound level (A-weighted)
L_{den}	Average sound exposure over the day, evening, and night-time period (A-weighted)
L_{dn}	Average sound exposure over the day and night-time period (A-weighted)
L_{max}	Maximum sound level (A-weighted) (s=slow)
L_{night}	Average sound level over the night-time period
LOAEL	Lowest observed adverse effect level
NNG	Night Noise Guidelines
NORAH	Noise-Related Annoyance, Cognition, and Health
Nx	Number of event noise metric
PSG	Polysomnography
RANCH	Road traffic and Aircraft noise effects on children's Cognition and Health
SATs	Standardised Assessment Tests
SEL	Sound exposure level
SOAEL	Significant observed adverse effect level
SoNA 2014	Survey of Noise Attitudes 2014 (UK)
SPL	Sound pressure level
TS	Technical Specification

Tx	Time above noise metric
UK	United Kingdom
WHO	World Health Organization
WHO ENG 2018	World Health Organization Environmental Noise Guidelines for the European Region 2018

Statement of Expertise

This report has been prepared by Charlotte Clark, Professor of Environmental Epidemiology, Population Health Research Institute, St George's, University of London, Cranmer Terrace, Tooting, London, SW17 0RE, United Kingdom.

Charlotte Clark gained her BSc (Hons) in Psychology from the University of Surrey in 1997 and her PhD in Environmental Psychology from the University of Surrey in 2001. She is a Chartered Psychologist and Fellow of the British Psychological Society; and a Member of the Institute of Acoustics (UK). Her areas of expertise are in the effects of environmental noise on health, wellbeing, and learning; the design and analysis of epidemiological research studies; and evidence review and synthesis in the field of noise and health.

Professor Clark is President of the International Commission on Biological Effects of Noise (ICBEN) and has advised the World Health Organization, the UK Department for Environment, Food and Rural Affairs, the UK Independent Commission for Civil Aviation Noise, the UK Department for Transport, the UK Civil Aviation Authority, and the International Civil Aviation Organisation (ICAO). She is currently Principal Investigator for the £1.7M UK Department for Transport study of the effects of aviation night noise on sleep and annoyance (The ANNE Study), producing exposure-response functions for UK policy. She is also Principal Investigator for studies evaluating the effectiveness of Heathrow airport's school and home noise insulation schemes on health and wellbeing and previously co-managed the European Union funded RANCH study (Road traffic and Aircraft Noise effects on children's Cognition and Health). She has produced influential evidence reviews on the effects of environmental noise on health, wellbeing and learning for the World Health Organization, the International Civil Aviation Organization and the Department for Environment (UK). She has advised on the noise and health impacts of large infrastructure projects (Heathrow Expansion) and airspace change. She is experienced at engaging with statutory consultees, communities and stakeholders. She has published over 80 papers in the field of environmental noise and health epidemiology and analysed National Noise Attitude Surveys.

Scope

Professor Charlotte Clark was commissioned by the Aircraft Noise Competent Authority in early 2025 to undertake an evidence review presenting the current state of the evidence for aviation noise effects on health covering the following health outcomes:

a. Annoyance
b. Sleep disturbance (subjective and objective sleep disturbance including awakenings);
c. Cardiovascular, metabolic disease, and mortality;
d. Stress, wellbeing and quality of life; and
e. Children's learning;

For each health outcome this report considers:

- The latest evidence from systematic reviews or robust large scale primary research studies and national surveys, as well as the evidence underpinning the World Health Organization aviation noise guidelines;
- Methodologies for defining policy thresholds for effects – along with consideration of evidence for thresholds for different aviation noise metrics (time-average noise exposure, number of events, maximum levels etc) and vulnerable population groups; and
- An overall conclusion as to the strength of the evidence for a negative effect of aviation noise on the health outcome.

Annoyance

Introduction

Annoyance is the most prevalent community response and health effect in a population exposed to aircraft noise, describing negative reactions to noise such as disturbance, irritation, dissatisfaction, and nuisance[1]. Annoyance has three components:

1) an often repeated disturbance due to noise;
2) an emotional and/or attitudinal response; and
3) a perceived lack of control or capacity to cope with the situation[2].

The European Environment Agency burden of disease assessment for noise effects in Europe 2025 estimated noise annoyance to be the most significant health effect of environmental noise (road, rail, aircraft noise)[3].

Environmental noise influences health by triggering biological responses in an individual. Annoyance is a stress response to noise. When sound enters the ears, it is also interpreted by the amygdala in the brain which handles endocrine and autonomic functions, and the 'flight or fight' response. If the amygdala is overactivated by noise the endocrine system will increase levels of the stress hormones cortisol and adrenaline, which are associated with mental ill-health. The sympathetic nervous system will also be hyperactivated, increasing heart rate and blood pressure, the production of inflammatory cells, and a change in blood fats and blood glucose [4,5]. These biological responses, if triggered over a long-time period (i.e., if exposure is chronic, over several years), are risk factors for cardiometabolic diseases such as type 2 diabetes, heart attacks, and strokes.

Noise metrics

Studies of noise annoyance use time-averaged metrics such as $L_{Aeq,16h}$ and L_{den} to summarise a 16-hour day-time period (07.00-23.00) or the whole 24-hour period. Number of events above a certain decibel (dB) sound level (Nx) can also be used, with N65 (number of events above 65dB) often used to characterise daytime exposure in the UK as part of airspace change proposals.

In the European Union, the L_{den} metric is the primary metric for measuring annoyance[3,6]. For studies of annoyance, the noise metrics reflect the sound level outside the individual's home, which are not able to take building attenuation and mitigation measures such as glazing and insulation into account. Night-time metrics have been used less often in relation to annoyance, where sleep disturbance is the preferred health outcome. However, some recent studies do examine annoyance during the night-time[7,8].

Measuring annoyance

The assessment of noise annoyance is undertaken using an International Organization for Standardization (ISO) Technical Specification (ISO/TS15666:2003 or

ISO/TS15666:2021)[9,10] which asks respondents about how "bothered, disturbed or annoyed" they have been by aviation noise over the past 12 months whilst in their home. Exposure-response functions (ERFs) showing the **'percentage highly annoyed' (%HA)** (derived from the ISO Technical Specification assessment) plotted against aviation noise exposure inform environmental and health impact assessments, as well as guidance and policy to protect public health. ERFs plot the probability of the %HA in the local population for a given dB noise exposure.

Types of Evidence

There are different types of evidence available to estimate the effects of aviation noise on public health. Different types of evidence have different uses and purposes.

Systematic reviews use systematic searching methods to identify all the individual research studies available for a particular noise exposure and outcome, e.g. aircraft noise and annoyance. Individual studies are also assessed for bias which might influence the review findings. If enough studies are identified, it is then possible to conduct **meta-analyses** which statistically combine the estimated effect of aircraft noise on %HA across the individual studies, enabling a more precise estimate of the effect and consistency across different studies to be estimated. This combining of the estimates produces a 'generalised' exposure-response function (ERF), reflecting the relationship across different contexts and populations. These combined estimates are particularly useful for burden of disease estimation[3].

In examining effects for an individual airport, the World Health Organization recommends using localised ERFs[6] where available, to assess the specific relationship between noise and the health outcome(s) of interest in a given situation. For example, Directive 2023/367 (amending Annex III of Directive 2002/49/EC the Environmental Noise Directive) indicates country specific ERFs could be used to estimate the health effects of noise[11]. Localised ERFs come from individual studies carried out in the local context, such as ERFs for specific airports or studies or from national surveys[7]. There are currently no local ERFs available for Dublin Airport or any national studies for Ireland. This means that assessments and regulation must revert to using generalised relationships as per the WHO.

Evidence for health effects of aviation noise on annoyance (% highly annoyed (%HA))

ERFs for aircraft noise effects on annoyance were published to inform the 2018 WHO Environmental Noise Guidelines (ENG) 2018[2]. This systematic review synthesised the evidence from 15 aircraft noise annoyance surveys published between 2000 and 2014 covering data from 17,094 respondents, living near very small to international airports with flight movements ranging from 34 to 1200 movements per day, estimating the %HA by L_{den}. The WHO ENG 2018 annoyance ERF suggested that 10% of the population were highly annoyed at 45dB L_{den}, 20% at ~52dB L_{den}, 30% at ~58dB L_{den}, and 50% at ~65dB L_{den}.

Based on this evidence, the WHO set guidance for aircraft noise annoyance at 45dB L_{den}, as that was where the combined data across the studies suggested 10% of the population were highly annoyed. Whilst this level of exposure is acknowledged to be low, evidence published over the past decade increasingly suggests that effects of aircraft noise on health may be observed even at low levels of exposure, compared with studies in the late 1990s and early 2000s which had focused on examining effects for exposures >=50dB.

Predicting or estimating annoyance at any given sound level has uncertainty, with the WHO ERF analysis indicating a wide range of estimates of annoyance for the same dB level of exposure across the studies included in the pooled analyses. For example, estimates for %HA at 65dB L_{den} range from ~18% to ~82% in the individual studies. Similarly, the %HA at 45dB L_{den} range from ~2% to ~28% in the individual studies. Uncertainty is also associated with methodological differences in survey design (sampling, format of the survey (e.g., face to face, online, post), recruitment, population, range of exposure) but also in terms of how noise exposure is estimated; operational differences between airports (e.g. number of runways, night-flights, availability of respite) and non-acoustic factors[12] (see below). This uncertainty, and the fact that effects clearly vary between contexts, is why the WHO recommend the use of local data to estimate effects, where available (World Health Organization, 2018).

The WHO ENG 2018 analyses found that aircraft noise was ranked as more annoying at the same dB level, than road traffic noise and railway noise. This reflects that noise annoyance depends not only on acoustic factors, but on a range of other factors, referred to as non-acoustic factors[13]. These could include aspects such as the fear associated with the noise source, interference with activities, ability to cope, noise sensitivity, expectations, anger, perceived control, perceived fairness, attitudes to the source – both positive or negative, and beliefs about whether noise could be reduced by those responsible influence annoyance responses[13,14]. Additionally, individual factors such as age, social disadvantage, and employment status[7,15,16] or other environmental factors, such as ambient/background noise levels can also be influential. Non-acoustic factors are particularly important and relevant for aviation noise.

Non-acoustic factors can considerably shift annoyance responses[7]. The UK Civil Aviation Authority's Survey of Noise Attitudes 2014 (SoNA 2014) found that high annoyance was associated not only with noise exposure, but also with noise sensitivity and expectations about aviation noise exposure next summer, which were powerful modifiers of the ERF for aircraft noise annoyance increasing the estimates for being highly annoyed in the population by 10 to 30%[7].

Acknowledging the importance of non-acoustic factors for community annoyance, the European Commission ANIMA project (Aviation Noise Impact Management through novel Approaches) concluded that to reduce noise annoyance, airports need to communicate with and engage with local communities and residents in the development, implementation, and evaluation of noise mitigation[17]. The study identified that attitudinal non-acoustic factors were best addressed by communication and engagement.

The WHO systematic review remains the most recent systematic review undertaken of aviation noise and annoyance at this time. The evidence for an effect of aviation noise on annoyance was rated as 'moderate' using the GRADE assessment[18], which means that the evidence is of moderate certainty, but that further research is likely to have an important impact on our confidence in the estimate of effect, and may change the estimate[18].

The WHO ENG 2018 ERF, and national ERFs, are 'steady-state' relationships which do not account for how people may respond if there is a change in aviation noise exposure. This has led to criticism of their use in assessments dealing with airport expansion or airspace change as they can underestimate the effect of a change in aircraft noise exposure on annoyance.

Studies examining distinct changes in aircraft noise exposure associated with communities becoming newly overflown, general airspace changes, or changes in runway operations, have found that there is an excess annoyance response in relation to the change in noise exposure, both for increases and decreases in exposure[19-23]. This is referred to as the **'change effect'**. This means that when noise exposure increases that the %HA response in the local population is slightly higher than would be predicted from steady-state ERFs for the actual noise exposure; conversely, when noise exposure decreases the %HA response in the local population is slightly lower than would be predicted from steady-state ERFs for the actual noise exposure. Studies suggest that these excess-responses are not temporary but can endure for at least a couple of years, if not longer[20,24]. Change effects have been observed in studies of communities experiencing relatively small increases in aircraft noise exposure e.g., 1-2 dB L_{den} as well as larger increases e.g., 5-7dB L_{den}.

There is some evidence that short-term changes in exposure associated with airport operation (e.g., runway alternation, operational modes) can also influence annoyance responses. The UK SoNA 2014 study found that respite, due to short-term changes in noise exposure associated with planned changes in operational modes and runway alternation at Heathrow airport, was associated with a reduced likelihood of being highly annoyed[25]. The study estimated exposure to aircraft noise exposure for two 8-hour daytime periods ($L_{Aeq,8h}$) (07.00-15.00 and 15.00-23.00), corresponding with operational modes and runway alternation, $L_{Aeq,8h}$ here refers to time-averaged aviation noise over an 8-hour daytime period and should not be confused with $L_{Aeq,8h}$ as used to define night-time noise exposure. Respite was defined according to the difference in noise exposure across the two daytime 8h periods. Respondents who experienced at least 9dB $L_{Aeq,8h}$ noise respite in the daytime were less likely to be highly annoyed, but this effect was not observed for those who received lower dB reductions across the two periods of the daytime. For residents experiencing no respite, 10% highly annoyed accorded with noise exposure of 52dB $L_{Aeq,16h}$. In comparison, for residents experiencing at least 9dB $L_{Aeq,8h}$ noise respite, 10% highly annoyed accorded with a noise exposure of 59.5dB $L_{Aeq,8h}$, a shift of 7.5dB $L_{Aeq,16h}$ for the same annoyance response.

In terms of **number above time-average metrics** (Nx), SoNA 2014 estimated that %HA rose from ~5% for 1-49 events >=65 dB L_{Asmax}, to 12-13% for 50-200 events >=65 dB L_{Asmax}, to 21% for 200-399 events >=65 dB L_{Asmax}, before falling to 14% for >=400 events >=65 dB L_{Asmax}. The lower %HA for the highest N65 value could reflect dwellings which have had noise insulation mitigation installed.[7] The SoNA 2014 report concluded that in terms of noise metrics $L_{Aeq,16h}$ correlated best with annoyance, but that there was merit in considering greater use of Nx metrics as supplemental indicators to help portray noise exposure to communities, recognising that for the UK context evidence-based decisions would continue to use $L_{Aeq,16h}$[7].

There are two large-scale ongoing studies of the effects of aviation noise on annoyance, which will report their findings in the next 6 months which could have relevance for the Irish context. The UK Civil Aviation Authority ANAS (Aviation Noise Attitude Survey) 2023-2024 is an update to SoNA 2014, albeit much larger, with a sample drawn from 10 UK airports exposed to 45dB $L_{Aeq,16h}$, with 3,000 responses per airport[26]. This will provide updated ERFs for day-time noise metrics and annoyance and examine a range of non-acoustic factors. The United Kingdom (UK) Department for Transport ANNE study (Aviation Night Noise Effects) will report on a survey of over 4,000 respondents living near 8 UK airports exposed to aviation night-noise[8]. This study will provide ERFs for annoyance at night, including ERFs for 1 hour time periods throughout the night-time for the first time, and will also examine non-acoustic factors. The ANNE study will also be able to compare annoyance at night with self-reported high sleep disturbance, to elucidate their relationship and potential overlap, which remains relatively unexplored. Both ANAS and the ANNE study examine lower levels of noise exposure than previous surveys.

Vulnerable groups

The European Environmental Agency concluded that *"exposure to environmental noise does not affect everyone equally. Socially deprived groups as well as groups with increased susceptibility to noise may suffer more pronounced health-related impacts of noise."*[27] It is hypothesised that those from lower socioeconomic status experience greater exposure to noise, which alongside increased vulnerability to poorer health, and the availability of fewer resources (coping behaviours) and poorer conditions (e.g., poor housing; less access to quiet areas) increases the risk for health related impacts of noise.

There is some evidence that certain population groups may be more likely to have higher rates of annoyance. Noise sensitivity, defined as "increased reactivity to sounds that may include general discomfort (annoyance or feeling overwhelmed) due to a perceived noisy environment, regardless of its loudness"[28] is associated with higher rates of psychological response to noise exposure including annoyance[7,27,29]. Surveys also suggest that middle-age individuals have higher noise annoyance responses compared with younger and older individuals[16]. This could relate to expectations around quiet, as well as exposure to other life stressors such as caring for children and elderly parents, and work stress. Pre-existing mental ill-health may also be a vulnerability factor, as annoyance and mental health have a cyclical relationship with each other[29-31]. Psychological ill-health may increase vulnerability by increasing time spent at home, sleeping outside of the night-time period or experiencing disrupted or extended sleep as a symptom of mental ill-health, and poorer coping capacities.

Interventions

A reduction in aviation noise exposure, whether via source, path, or infrastructure interventions[19], should reduce impacts on annoyance. However, empirical evidence quantifying the effect or undertaking cost-benefit analysis is scarce[19]. Despite insulation being one of the most common interventions offered to local communities experiencing the highest exposures to aircraft noise, there have been few studies that quantify the effect on the health and quality of life of residents.

A before and after study being undertaken for Heathrow Airport is evaluating the effect of the new package of residential insulation offered under its Quieter Neighbourhood Support scheme on health, quality of life and wellbeing. The study assesses changes in noise annoyance, subjective sleep disturbance, and wellbeing 3-months and 12-months post installation of the insulation.

The Quieter Neighbourhood Support scheme focuses on residential receptors experiencing the highest levels of aviation noise around the airport, determined by a composite contour reflecting the SOAEL for day and night, scheduled operations before 06:00, the Sound Exposure Level (SEL) footprint of the noisiest aircraft, and the calculated probability of >1 additional awakening[32]. The scheme provides up to £34,000 per property to cover 100% of eligible costs.

Analysis of the pilot study data identified a significant reduction in annoyance 3-months post installation of the noise insulation in residents' homes[33]. At baseline 59% of the sample were HA during the night-time, and 68% in the daytime and 24-hour period, respectively. There was a statistically significant reduction in the proportion of the sample HA from baseline to 3-month follow-up with 22% HA for the night-time, 17% HA for the daytime period, and 15% HA for the 24-hour period.

The study is ongoing and analysis of the 12-month follow-up data will be published in late 2026, along with a cost-benefit analysis of the noise insulation scheme for health, quality of life and wellbeing. The magnitude of effects observed for the change in annoyance was large in the preliminary analyses, suggesting that the intervention has the potential to significantly protect public health for those experiencing the highest levels of noise exposure. However, the magnitude of the effect seen is likely to be large because of the amount of investment in the scheme, per property. A scheme, such as this, is focused and appropriate for those with the highest level of aviation noise exposure only, and would not be appropriate or cost-effective for those experiencing lower levels of aviation noise exposure. To date, studies examining the effectiveness of lower cost mitigations, which could be applied to those with lower levels of aviation noise exposure are limited to sleep disturbance[34].

The aircraft noise criteria informing eligibility for airport residential insulation schemes have steadily decreased over the past two decades, with recent schemes typically offering insulation at around ≥60dB based on noise metrics covering the day-evening-night time period [35]. This reflects the increasing evidence over time for significant elevated health risks at these levels[3]. Residential insulation schemes mitigate the effects of aircraft noise on health, but do not avoid all the health impacts. Noise will still be experienced outside of the property; noise may still be heard inside the property – albeit at a lower exposure but at an exposure which could still contribute to adverse health effects; and people may still experience some annoyance due to the role of non-acoustic factors in response. Hence, noise insulation schemes ameliorate but do not remove all the effects of aircraft noise effects on health in a population.

Summary for Annoyance

- Annoyance is an accepted public health issue for those exposed to aviation noise.
- There is good evidence that time-averaged aviation noise across the daytime and 24h period is associated with annoyance through metrics such as the L_{den}.
- Annoyance response influenced by many factors other than the noise exposure, per se. These non-acoustic factors include individual, social and environmental factors.
- When aircraft noise exposure increases there is a stronger annoyance response than would be predicted, even when the change in noise is relatively small (e.g., 1-2dB).
- Groups with additional vulnerable to the effects of annoyance include those with noise sensitivity, poor mental health, and those in middle-age.
- Emerging evidence supports a significant effect of residential noise insulation on reducing annoyance for those with the highest levels of exposure.

Sleep Disturbance

Introduction

Sleep is fundamental for good health and requires adequate duration, good quality, appropriate timing and regularity, and the absence of sleep disturbances or disorders[36]. It is recommended that to promote optimal health that adults should get seven to eight hours sleep each night[36,37].

The European Environment Agency burden of disease assessment for noise effects in Europe in 2025 estimated sleep disturbance to be the second most significant health effect of environmental noise, after noise annoyance[3].

Noise metrics

Studies of sleep effects of noise can use traditional **time-averaged metrics** such as $L_{night,outside}$ as used by the World Health Organization[6,37] and the Environmental Noise Directive (END)[11] to summarise the whole 8-hour night-time period (23.00-07.00). However, as aircraft noise exposure at night can also be viewed as a series of intermittent events, studies have also use **event-based metrics** assessing discrete noise events such as L_{Amax}. Number of events above a certain dB sound level during the 8-hour night-time period (Nx) is also used. The noise metrics, whilst predominantly reflecting the sound level outside the individual's home, can also be indoor metrics, which are able to take building attenuation and mitigation measures such as glazing, window opening, and insulation into account.

Measuring sleep

Measuring sleep is challenging as there is no one physical or psychological measure which encapsulates sleep processes. Studies of aircraft noise effects on sleep have examined two types of sleep outcome: subjective (self-reported sleep disturbance) and objective sleep disturbance.

Subjective (self-reported) sleep disturbance is assessed using questionnaires or diaries about an individual's perceptions of waking up during the night, the amount of time taken to fall asleep (sleep latency) and other perceptions of sleep quality, which are then related to external time-average noise metrics assessed over several hours such as $L_{Aeq,8h}$ or L_{night}. If collected as part of a field study that includes internal noise exposure assessment in the bedroom, then the comparison can be made with indoor time-averaged noise metrics.

Objective sleep disturbance is assessed by recording biophysiological changes that occur during sleep and changes in sleep stages (e.g., awakenings, body movement, increases in heart rate and blood pressure), which are then related to event-based noise metrics such as indoor or outdoor L_{Amax} (e.g., did an aircraft event of a certain loudness lead to an awakening), as well as time-average metrics (e.g., does the number of awakenings during the 8-hour night period relate to the average noise exposure for that source over the 8-hour night period). A 'biological awakening is defined as an individual moving from deeper sleep stages to lighter sleep stages defined as 'sleep stage 1' or 'awake'. The 'Gold Standard' methodology for assessing sleep, and objective sleep disturbance, is polysomnography (PSG) which records biophysiological changes that occur during sleep by measuring brainwaves, eye movements, muscle activity, limb movements and heart rate[38]. However, PSG is costly and time intensive to conduct and analyse, so some recent studies have adapted the approach to measure objective sleep disturbance based on heart rate and 'actimetry' (movement) data, including the ongoing United States Federal Aviation Authority funded National Sleep Study[39], and the ongoing United Kingdom Department for Transport funded ANNE study[8]. Both studies also assess subjective sleep disturbance. Actimetry data, which assess physical movements during sleep[40], can provide approximations of awakenings, arousals, sleep onset time, total sleep time and sleep efficiency[41]. Objective sleep disturbance outcomes can be related to either external or internal noise exposure.

Additional aircraft noise induced awakenings[42], a marker of objective sleep disturbance, is also used as an outcome. This measure, based on PSG study evidence[42], plots the awakening probability with increasing maximum SPL (Sound Pressure Level) L_{Asmax} of the aircraft noise event, with the number and noise level of each aircraft event occurring during the night-time period, to estimate the number of average nightly aircraft noise induced awakenings[42,43].

Both objective and subjective sleep disturbance measures have a role to play in understanding the effect of aviation noise on local populations and can be assessed in the field (i.e., within an individual's home environment) or in the laboratory (where noise exposure and events can be more controlled).

Subjective reports may differ from objective reports for many reasons. Individuals are unconscious for most of the time they are asleep so may not be aware of their sleep disturbance; may misattribute awakenings for other reasons (e.g., children, partners, pets, neighbours) to aircraft noise events; and may make subjective reports to indicate dissatisfaction and annoyance with their noise exposure and the airport operator.

Evidence for health effects of aviation noise on objective sleep disturbance

ERFs for aircraft noise effects on objective sleep disturbance were published to inform the WHO ENG 2018[44]. Based on systematic review evidence of studies using PSG, there was a significant positive association between indoor maximum noise levels of single events and the probability of sleep stage transitions to wake or Stage 1 (an awakening). The probability of awakening for a 10dB increase in the indoor L_{Asmax} increased significantly for aircraft noise by 35% (95% confidence interval 33%-50%). The noise level at which the probability of an additional awakening began was around 37-38dB L_{Asmax} indoor, however the authors stated that this was not a LOAEL value (Lowest Observed Adverse Effect Level) – i.e., a threshold indicating where effects begin. This statement might imply that a LOAEL value would be lower, but the intent of the authors is not clear.

The WHO systematic review remains the most recent systematic review undertaken of aviation noise and objective sleep disturbance. The evidence for an effect of aircraft noise on objective sleep disturbance was rated as ‘moderate’ using the GRADE assessment[18] in both the review[44], which means that the evidence is of moderate certainty but that further research is likely to have an important impact on our confidence in the estimate of effect, and may change the estimate[18]. The review authors acknowledged that to date, most of the evidence for objective sleep disturbance comes from studies of healthy subjects, with no pre-existing health problems or sleep disorders[44].

In an earlier study, Basner found that awakening probability increases with the maximum SPL (Sound Pressure Level) L_{Asmax} of the aircraft noise event, and that the number of events needed to induce an additional awakening increased as the SPL decreases[42]. Further, the time taken to fall back to sleep was also influenced by the maximum SPL, but only for events 70dB or higher L_{Asmax}.

Few studies have examined the effect of a change in aviation noise on objective sleep disturbance. The NORAH study around Frankfurt Airport found that people woke up less frequently after the introduction of night-flying restrictions (23.00-05.00) and the opening of the new North-West runway[45]. The NORAH study also demonstrated that awakenings were fewer when background noise was louder (as the difference between the aircraft noise event and the background was reduced).

It is often assumed that people exposed to transportation noise at night adapt or habituate, so essentially get used to the noise exposure. Laboratory studies provide evidence that some habituation does occur, as individuals are more likely to wake up in a sleep lab than in their own home and awakening probabilities decrease across nights in the lab. However, habituation is not complete, as people are still woken up by noise in their own home, and beyond awakenings, other biological responses that impact health, such as heart rate, habituate to a lesser degree[46].

In summary, single aviation noise events can directly break sleep by inducing awakenings which can shift sleep to being less restorative, decreasing deep sleep and increasing time awake[46]. Evidence suggests that aviation noise events later into the sleep period and nearer to the end of night-time are more likely to influence objective sleep disturbance[42,47,48], as once people are less tired they are more likely to wake and also be less likely to fall back to sleep again. The effects of aviation noise on objective sleep disturbance are established and accepted as a public health issue.

There are two large-scale ongoing studies of the effects of aviation noise on objective sleep, which will report their findings in the next 12 months. The Federal Aviation Authority’s (FAA's) National Sleep Study[39] led by Basner, will examine the effect of night-time aviation noise for 400 participants selected across 77 US airports recording ECG, body movement and sound pressure levels in the bedroom for 5 nights. The United Kingdom (UK) Department for Transport ANNE study (Aviation Night Noise Effects) led by Clark, uses the same methodology as the FAA study, collecting data for over 200 participants from 8 UK airports for 7 nights[49]. Both studies will produce ERFs for A-weighted sound pressure levels of individual aircraft noise events measured inside in the bedroom and awakening probability inferred from changes in heart rate and body movement, adding substantially to the evidence base for use in health and environmental impact assessments.

Evidence for health effects of aviation noise on subjective sleep disturbance

ERFs for aircraft noise effects on subjective sleep disturbance (assessed using self-report questions about falling asleep, awakenings, and sleep quality) were published by the systematic review undertaken to inform the WHO ENG 2018[44], which found that around 10% of the population are highly sleep disturbed (HSD) at 40dB L_{night}, 20% at 50dB L_{night}, rising to over 30% for exposures over 55dB L_{night}.

The systematic review for subjective sleep disturbance was subsequently updated in 2022[50]. The updated review of 15 individual studies also concluded that aircraft noise was significantly associated with subjective sleep disturbance. Around 10% of the population are highly sleep disturbed at 40dB L_{night}, 20% at 47dB L_{night}, rising to over 30% for exposures at 54dB L_{night}. The 2022 review concluded that safe levels for aviation noise at night were 40dB L_{night} and that the existing WHO guidelines did not need revising[6,37].

The 2022 systematic review remains the most recent systematic review undertaken of aviation noise and subjective sleep disturbance. In terms of certainty of the evidence, the evidence for an effect of aviation noise on subjective sleep disturbance for questions mentioning noise was rated as 'moderate' using the GRADE assessment[18] in both the earlier[44] and updated review[50], which means that the evidence is of moderate certainty, but that further research is likely to have an important impact on our confidence in the estimate of effect, and may change the estimate[18]. The evidence for an effect of aviation noise on subjective sleep disturbance for questions which did not specifically mention noise was rated as 'low quality' in both the earlier[44] and updated review[50], which means that the evidence is uncertain and that further research is very likely to have an important impact on our confidence in the estimate of effect and is likely to change the estimate[18].

In terms of evidence for effects for additional aviation night noise metrics, analyses of the SoNA 2014 found that N60 (number of events above 60dB L_{Amax} during the night-time period) was associated with HSD. 10% of the population were HSD with 20-29 events per night, 18% with 30-39 events per night, and 14% with more than 40 events per night[51]. However, whilst describing the outcome as HSD, SoNA 2014 used the ISO/TS15666 annoyance measure[52] which is not a measure of sleep disturbance. This more likely reflects night-time annoyance. The Department for Transport ANNE study will shortly report ERFs for both HSD and HA during the night-time (23.00-07.00h), as well as ERFs for one-hour periods throughout the shoulder and night-time periods (21.00-08.00h) based on a survey of over 4000 residents living near 8 UK airports[49], adding to the existing evidence base for health and environmental impact assessments.

Further analyses of the UK SoNA 2014 data, using contours plotting one-additional aircraft noise induced awakening as a noise metric, suggested that one additional awakening was associated with 10% HSD, two additional awakenings with 15% HSD, and three or more additional awakenings with 20% HSD[43]. Again, these findings are based on the annoyance at night measure and not HSD, per se. Additional awakenings correlated well with $L_{Aeq,8h}$ and L_{night}, and the self-reported sleep disturbance findings, suggesting that "the concerns that are expressed that averaging the night-time noise exposure does not properly reflect the impact of individual aircraft noise events may be unfounded"[43].

Overall, the evidence for an impact of change in aircraft noise on subjective sleep disturbance is mixed, with some studies including the NORAH study, finding little change in self-reported sleep disturbance after operational changes[24,48,53-55] and others suggesting that an increase or decrease in noise was associated with changes in subjective sleep disturbance[21]. A study around La Guardia airport before and after a change in flight paths suggested increased diagnoses of insomnia, with the effect being greatest for children aged 5-17 years[56]. Whilst the evidence is currently limited with mixed findings, it should not be discounted that operational changes can cause subjective sleep disturbance.

Vulnerable groups

In terms of sleep specifically, there is limited empirical evidence, to date, about whether certain population groups may be more likely to have their sleep influenced by aviation noise events. This means that considerations of vulnerability are currently theoretical, rather than evidenced by research studies.

It has been hypothesised that older age, poorer hearing and noise sensitivity may be vulnerability factors[57], along with pre-existing cardiovascular disease[58] and shift-work[59]. Reasons for increased vulnerability include; increased risk for poorer health, spending more time at home, sleeping at times outside of the typical night-time period, and poorer coping capacities.

Given how physical and mental health can impact sleep it is plausible that those with existing ill-health may be particularly vulnerable to the effects of aviation noise on sleep. Children may also be particularly sensitive, as they have earlier bedtimes and sleep for longer time-periods, which may overlap with periods of high aircraft traffic which are not included in metrics such as L_{night}[60]. However, research studies are needed to confirm which population groups are vulnerable to the effects of aviation noise on sleep.

Interventions

The evaluation of Heathrow Airport's Quieter Neighbourhood Support scheme has also examined changes in subjective sleep disturbance 3-months post installation[33]. Rates of being 'highly sleep disturbed' (HSD) decreased markedly at the 3-month follow-up, with 46% being HSD at baseline and 15% at 3-month follow-up. Analyses of the 12-month follow-up data will be published in late 2026, along with a cost-benefit analysis of the noise insulation scheme for sleep disturbance.

As previously argued, the magnitude of effects observed for the change in subjective sleep disturbance are large in the preliminary analyses, suggesting that if this finding is maintained across a larger sample size, that the intervention has the potential to significantly protect against sleep disturbance but is costly and appropriate for those with the highest levels of exposure.

A recent study examined the effectiveness of lower cost mitigation for environmental noise exposure in a laboratory study, assessing the use of pink noise and ear plugs on objective sleep disturbance[34]. The study found in a sample of 25 subjects that earplugs mitigated nearly all the effects of environmental noise on sleep but started failing at the highest level of exposure (65 dBA). In contrast, pink noise did not mitigate effects and worsened sleep, particularly impacting Rapid Eye Movement (REM) sleep. Mitigations such as the use of ear plugs could be focused on populations exposed to moderate levels of aviation noise.

Whilst the aircraft noise criteria informing eligibility for airport residential insulation schemes have steadily decreased over the past two decades, few schemes to date base eligibility on night-time metrics, but instead use the day-evening-night time period [35]. Given the increasing evidence for the effects of aviation noise on sleep disturbance, both subjective and objective, eligibility should take night-time exposure specifically into account to protect from sleep disturbance. As previously discussed, residential mitigation should reduce the effects of aviation noise on health, but not remove all the effects, as some noise exposure may remain.

Summary for Sleep Disturbance

- Sleep is an accepted public health issue for those exposed to aviation noise.
- There is good evidence that time-averaged aviation noise is associated with subjective sleep disturbance as measurable through metrics such as L_{night} and $L_{Aeq,8hr}$.
- There is good evidence that event-based aviation noise is associated with objective sleep disturbance (awakenings).
- People do not completely habituate to aircraft noise in their homes: objective sleep disturbance responses are observed for residents who have lived in their homes for many years.
- Interventions such as insulation are an important public health measure for night-time noise effects as habituation is not complete, and individuals respond to the internal noise events and exposure in their bedrooms.
- There are few studies of the effect of change in aviation noise on sleep disturbance.
- Groups with additional vulnerability to the effects of aviation noise on sleep disturbance include children, those with poor physical and/or mental health, older adults, noise sensitivity, and shift-workers.
- Time-averaged metrics are sufficient to describe the public health impacts of night-flights on subjective sleep disturbance and remain a robust approach for quantifying these effects.
- Emerging evidence supports a significant effect of residential noise insulation in reducing subjective sleep disturbance for those with the highest levels of exposure, as well as the effectiveness of ear plugs in reducing objective sleep disturbance for those exposed to moderate levels of aviation noise.

Cardiovascular and metabolic diseases, and mortality

Introduction

The importance of cardiovascular disease and type 2 diabetes is well established, with both having a considerable disease burden and being leading causes of death, worldwide[61,62]. Risk factors for these diseases include genetic and lifestyle factors, but it is increasingly acknowledged that environmental factors, including long-term environmental noise exposure contribute to risk[63].

The European Environment Agency burden of disease assessment for noise effects in Europe in 2025 estimated that as well as contributing to 50,000 new cases of cardiovascular disease and 22,000 new cases of type 2 diabetes, noise was linked to at least 66,000 premature deaths per year – that is around 1.1% of premature deaths per year in Europe[3].

Noise metrics

Studies of noise effects on cardiovascular and metabolic outcomes use time-averaged metrics outdoor metrics such as L_{den}, L_{day}, and L_{night}. Given that cardiovascular and metabolic diseases take many years to develop, studies are increasingly using time-averaged metrics summarised over 5 to 20 years to establish the relationship between noise exposure and the onset of disease. Laboratory based studies focusing on mechanisms for effects or short-term cardiovascular responses to noise exposure (e.g. increased heart rate) use shorter-time periods for the time-averaged metrics. Number of events above a certain dB sound level (Nx) are scarcely examined in relation to cardiovascular and metabolic outcomes, nor are event-based metrics assessing discrete noise events such as $L_{Amax.}$ The latter may be used in some laboratory, mechanistic studies.

Measuring cardiovascular and metabolic disease

Cardiovascular disease is a term used to describe a range of health conditions relating to circulation and the heart, including Coronary Heart Disease (CHD), Ischaemic Heart Disease (IHD), Angina, Acute Myocardial Infarction (AMI) – a heart attack, atrial fibrillation (AF) (heart rhythm problems), Heart Failure, and Stroke. Many of these different cardiovascular conditions have atherosclerosis in common, that is, a build-up of blood fats (atheroma) overtime that cause arteries to become narrowed. If a piece of atheroma breaks away in the artery it may cause a blood clot to form, which may block the coronary artery cutting off supply of blood to the heart muscle, causing a heart attack. When a blood clot blocks an artery that carries blood to the brain, this causes a stroke. Arteries can also be damaged by persistently high blood pressure (hypertension), which also puts a strain on heart muscles, increasing the risk of a heart attack or stroke.

Insulin is a hormone required to allow glucose to enter cells or to be stored; Type 2 diabetes is diagnosed when the body doesn't make enough insulin or cannot use the insulin it produces. This causes raised glucose levels over time in the blood stream, which leads to other health complications, damaging the heart, kidneys, nerves, and eyes.

It can be challenging to understand how soundwaves in the environment can, over time, lead to serious cardiovascular and metabolic disorders, and premature mortality. There are three pathways by which noise can influence cardiometabolic health. The first is through the stress pathway. If sound is interpreted as a stressor, it triggers a cascade of reactions in the body via the flight or fight response. This activates the sympathetic nervous system, quickening heart rate, raising blood pressure, changing blood glucose and blood fats, and triggering the production of inflammatory cells which cause vascular and cerebral inflammation. The stress pathway also activates the hypothalamic-pituitary-adrenal (HPA) axis, increasing stress hormones such as cortisol. Chronic stress causes dysregulation of the HPA axis, which is associated with high blood pressure, blood glucose, insulin resistance, vascular damage, and inflammation. In the past few years, evidence has become available from human studies[64] and animal studies[65-67] to support the effects of noise via these biological pathways. Some of these pathways are also implicated in the effects of air pollutants on cardiovascular disease and mortality, with studies of noise adjusting for co-occurring air quality measures[68].

The second pathway is sleep. Whilst poor sleep is a stressor in its own right, individuals are programmed, via the flight or fight response, to respond to noise, with the sympathetic nervous system and HPA system responding to noise during sleep.

The third pathway is effects on lifestyle factors that directly contribute to cardiovascular and metabolic disease development. Stress responses to noise might influence diet (food intake, alcohol) and exercise; further people may also be less likely to exercise in noisier neighbourhoods. A study also found that noise annoyance was associated with lower levels of physical activity[69].

Evidence for health effects of aviation noise on cardiovascular and metabolic disease, and mortality

The systematic review and meta-analyses examining the evidence for noise effects on cardiovascular and metabolic health outcomes to inform the ENG 2018 reviewed studies of aircraft noise exposure and hypertension, ischaemic heart disease, stroke, and diabetes[70]. Since 2018 further updated meta-analyses have been published[71-73]. The most recent review undertaken to inform the European Environment Agency's Noise in Europe 2025[3] burden of disease estimates, highlighted how evidence for effects of transportation noise on the development (incidence) of cardiovascular and metabolic disease has increased substantially[72], with the field moving beyond examining ischaemic heart disease to include stroke, diabetes, heart failure and hypertension in relation to cardiovascular disease. Recent studies have also included the examination of mortality[3,74,75]. The European Environment Agency review is a comprehensive up-to-date review of the field.

Table 1 summarising the European Environment Agency's most recent estimates for the effect of a 10dB L_{den} increase in aircraft noise exposure for cardiovascular and metabolic health outcomes, along with the GRADE rating of the strength of the evidence. Most of the estimates for aircraft noise indicate a slightly increased risk for a 10dB L_{den} increase in aircraft noise, ranging from no increase in risk for stroke, a 1% increase in risk for IHD, a 6% increase in risk for heart failure, an 8% increase in risk for hypertension, a 12% increase in risk for type 2 diabetes, and a 20% increase in risk for arrythmia. However, with the exception of heart failure, none of the estimates are statistically significant (i.e., the 95% confidence intervals include the value of 1.00).

For IHD, heart failure, hypertension, and type 2 diabetes, the evidence for aircraft noise is rated as 'low', which means that the evidence is uncertain and that further research is very likely to have an important impact on our confidence in the estimate of effect, and is likely to change the estimate[18]. For stroke and hypertension, the evidence is rated as 'very low', which means that there is little confidence in the estimated effect and that the true estimate is likely to be substantially different from the estimated effect. The evidence for some of the cardiovascular effects of aircraft noise exposure is currently limited[76].

The European Environment Agency review notes the uncertainty for estimates of the effects particularly for aircraft noise, in comparison to the evidence for road traffic noise, and proposes, that whilst further evidence is collected, that health impact assessments (HIA) should use the estimates for road traffic noise. It is further suggested that a combined estimate for cardiovascular diseases is used, rather than estimates for individual cardiovascular disease outcomes. The European Environment Agency concluded that "the relationships for road traffic noise are proposed to be used to estimate the impacts of rail and aircraft traffic noise on all-cause mortality, cardiovascular diseases and diabetes. It is plausible that biological mechanisms are similar for various transportation noise source."

These recommendations are summarised in Table 1, indicating that the ERFs for use in HIA suggest that a 10dB L_{den} increase in noise is associated with a 6% (95%CI 3-8%) increase in risk for type 2 diabetes, a 3% (95%CI 1-5%) increase in risk for cardiovascular disease, and a 5% (95%CI 1-6%) increase in risk for premature mortality. These increased risks are moderate compared to some other risks for cardiometabolic ill-health but can be important where a large population, and vulnerable groups, are exposed. The European Environment Agency justify the mortality, and cardiovascular and metabolic health outcomes proposed to be considered in HIA, along with annoyance, sleep disturbance, and children's learning impairment, as being outcomes where there is reasonable evidence for a causal relationship between noise exposure and the health outcome.

Table 1: summary of the 2025 European Environment Agency (EAA) estimates for the effect of a 10dB L_{den} increase in transportation noise on cardiovascular and metabolic disease, and mortality.

Health outcome	Aircraft noise		Recommended by the EEA for use in HIA
	Relative risk (95%CI) per 10dB L_{den} increase	Evidence rating	Relative risk (95%CI) per 10dB L_{den} increase
IHD	1.01 (0.99-1.02)	Low	Use incidence CVD estimate
Stroke	0.99 (0.87-1.13)	Very low	
Heart failure	1.06 (1.04-1.08)	Low	
Hypertension	1.08 (0.97-1.19)	Low	
Arrythmia	1.20 (0.69-2.08)	Very low	
Type 2 diabetes	1.12 (0.83-1.05)	Low	1.06 (1.03-1.08)
Mortality	-	-	1.05 (1.01-1.06)
CVD (incidence)	-	-	1.03 (1.01-1.05)

There has been less focus on identifying LOAEL and SOAEL (Significant Observed Adverse Effect) values in relation to cardiovascular and metabolic outcomes, with most values and guidance informed by effects on sleep disturbance and annoyance. However, as previously described, the European Environment Agency highlighted that annoyance and sleep disturbance are both also a pathway to cardiometabolic diseases[27], supporting the idea that addressing annoyance and sleep disturbance will address other health outcomes in the local population.

More recently, the European Environment Agency also noted that "the new body of evidence shows negative effects due to transport noise at much lower levels than those captured in the END exposure assessments (i.e. 55 dB L_{den}, and 50 dB L_{night}). Therefore, health risks of noise should be quantified at levels starting at 45 dB L_{den} and 40 dB L_{night}". A recent publication highlighted that shifting the threshold from 55dB L_{den} to 45dB L_{den} tripled the estimated number of noise-related IHD and CVD deaths in studies carried out in Denmark and Switzerland[76], further supporting the setting of a LOAEL value for cardiovascular effects below 50dB L_{den}.

Multiple exposures to transportation noise may also be important when considering aviation noise in relation to cardiovascular and metabolic disease. A nationwide Danish study found that the increased risk of 10 years transportation noise exposure on developing type 2 diabetes was greater for those exposed to two or more noise sources (e.g., road, railway, aircraft) than for those exposed to one noise source[77].

Whilst most studies examine the hypothesis that it is long-term exposure to aircraft noise which influences the development of cardiovascular and metabolic disease, and subsequent mortality, evidence is starting to emerge which suggests that short-term aircraft noise exposure might also be a trigger for cardiovascular events and mortality[78]. A study of over 24,000 cardiovascular deaths around Zurich airport between 2000-2015 found that aircraft noise exposure two hours preceding death were associated with mortality. Risk of death increased by 44% (95%CI 3-104%) for those with aircraft noise exposure L_{Aeq} >50dB compared with <20dB[78]. However, a study of 442,000 cardiovascular hospital episodes or deaths around Heathrow airport between 2014-2018 found a very small increased risk for cardiovascular disease hospital admissions for aircraft noise exposure between 19.00-23.00 hours, with risk increasing by 0.05% (95%CI 0-1%) per 5dB increase in aircraft noise[79], but did not find effects for noise exposure at other times of the day or night, or with mortality.

Evidence is emerging to support a relationship between environmental noise and neurodegenerative outcomes and cognitive impairment such as dementia in later life [80], which could be explained by damage to blood vessels in the brain (e.g., vascular dementia) or via inflammation associated with stress. However, evidence has yet to emerge specifically for aircraft noise as an exposure, and the recent European Environment Agency report did not include dementia in their current recommendations for HIA[3].

The findings and focus of the 2025 European Environment Agency report change the rhetoric around aviation noise effects on health. The shift in focus to mortality, beyond the traditional consideration of individual disease endpoints turns the dial. Stakeholders are likely to increasingly make, or come up against, the argument that chronic noise exposure can kill.

It has been hypothesised that individuals might adapt or habituate to exposure to environmental noise, which would mean that cardiovascular and metabolic responses would lessen or reduce in magnitude over time. However, studies suggest that habituation in terms of cardiovascular responses does not occur over the night-time period [81] and that effects are stronger for individuals who have lived in their residence for a longer time period[82]. Few studies have quantified the effect of a longer-term change in aircraft noise exposure on cardiovascular and metabolic responses: the NORAH study failed to demonstrate a change in blood pressure for residents after one year when residential aircraft noise increased or decreased in association with changes in airport operation and the opening of a new runway[83]. It is possible that a longer time period might be needed to observe effects, but further studies are needed of change in noise exposure on cardiovascular and metabolic health.

Vulnerable groups

Specifically considering vulnerability for the effects of aircraft noise on cardiovascular and metabolic disease, and mortality, there are ethnic inequalities in risk factors for these diseases. Cardiometabolic diseases are more common in individual's from South Asian and Black ethnic groups[84] and ethnic minorities tend to be exposed to higher levels of environmental noise [85,86], both of which may increase vulnerability. There is also evidence that noise stress on top of existing cardiovascular disease or risk may accelerate the process of vascular and cerebral atherosclerosis (narrowing of the arteries) and neurodegenerative disease such as vascular dementia[67,76]. Existing ill-health may increase vulnerability by increasing time spent at home or sleeping outside of the night-time period.

Summary for Cardiovascular and Metabolic Disease & Mortality

- Cardiovascular and metabolic diseases are accepted public health issues for those exposed to aviation noise, which lead to premature mortality.
- There is evidence that time-averaged aviation noise is associated with a range of cardiovascular outcomes, and Type 2 diabetes, however, there is uncertainty in the magnitude of the effects.
- Aircraft noise influences these health outcomes via the autonomic nervous system, HPA axis, sleep, and lifestyle factors, contributing to disease risk factors such as narrowing of arteries and high glucose levels.
- People do not habituate to aircraft noise in their homes: cardiovascular and metabolic responses to noise at night continue for those exposed to aviation noise for many years.
- There are few studies of the effect of change in aviation noise on cardiovascular and metabolic disease.
- Groups with additional vulnerability to the effects of aviation noise on cardiovascular and metabolic disease include those with existing cardiovascular ill-health, and South Asian and Black ethnic groups who have increased risk for these outcomes, per se.
- Guidelines that address sleep disturbance and annoyance should also protect cardiovascular and metabolic health.

Mental health, wellbeing, and quality of life

Introduction

Noise as an environmental stressor can also impact mental health, wellbeing, and quality of life, both directly through influencing stress hormones which impact mood, but also indirectly through stress associated with annoyance and sleep disturbance.

The European Environment Agency burden of disease assessment for noise effects in Europe in 2025 estimated that transportation noise accounted for 0.8% of all new cases of depressive disorders in Europe.[3].

Noise metrics

Studies of the mental health, wellbeing, and quality of life effects of noise predominantly use traditional time-averaged metrics such as L_{day}, L_{den}, $L_{night,outside}$ to summarise various time periods over 24-hours. The noise metrics predominantly reflect the sound level outside the individual's home. Studies rarely examine number of event metrics (Nx) or event-based metrics assessing discrete noise events such as L_{Amax}. Studies of children tend to use time-averaged metrics of aircraft noise exposure calculated for either or both the home or school environments.

Measuring mental health, wellbeing, and quality of life

Mental health, wellbeing, and quality of life are related but distinct constructs. The World Health Organization defines mental health as "a state of mental well-being that enables people to cope with the stresses of life, realize their abilities, learn well and work well, and contribute to their community"[87]. In studies of noise and health, mental health for adults is usually defined in terms of the presence or absence of psychological or psychiatric ill-health such as depression and anxiety based on diagnoses assessed by doctors/medics using standardised diagnostic instruments; identified from medical records; from self-reports of having have received a diagnosis, or from symptom scales. Some studies examine medication use for anxiety and depressive disorders, or biological markers for mental ill-health such as cortisol which is an indicator of stress. However, medication studies could potentially be less robust as the majority of individuals with depressive and/or anxiety disorders do not take medication. Some recent studies examine suicide, where suicide is an indicator for mental ill-health as opposed to noise being causally related to suicide, per se. Depression is the most studied outcome, and effects on other types of common mental diagnoses such as phobias or psychoses have rarely been examined.

For children, mental health is often defined in terms of internalizing problems (emotional symptoms, depression and anxiety, peer-relationship problems) and externalizing problems (symptoms of conduct problems and hyperactivity). The focus is often on symptoms and not diagnoses. Many studies use the Strengths and

Difficulties Questionnaire[88] which assesses internalizing and externalizing problems, as well as a total difficulties score, which combines internalizing and externalizing problems. Some studies also examine diagnoses of ADHD (Attention Deficit Hyperactivity Disorder).

Wellbeing as a concept defines how individual's evaluate their own lives, including life satisfaction, sense of purpose and meaning, and emotional state[89]. Wellbeing can be assessed using self-report measures, but few studies of noise and health have specifically examined wellbeing as an outcome.

The World Health Organization defines quality of life as "an individual's perception of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns"[90] Studies of noise and health use self-report questions to assess quality of life.

Mental health, wellbeing, and quality of life are impacted by a range of other factors and stressors such as socioeconomic status, age, gender, physical health, and exposure to other life, work and home stressors. Therefore, studies examining the influence of aviation noise on mental health, wellbeing, and quality of life take into account a large number of factors that might also influence these outcomes. Past history of mental ill-health is also a powerful determinant, to be considered.

Evidence for health effects of aviation noise on mental health, wellbeing, and quality of life

The WHO Environmental Noise Guidelines (ENG) 2018 undertook a systematic review of the evidence for effects of aviation noise on mental health[91], however, this review, and a subsequent update[92], were unable to publish exposure-response functions (ERFs) for aircraft noise effects on mental health due to the variety in methods and measures used across the available evidence.

The recent 2024 review undertaken for the European Environment Agency[93] is the most recent systematic review undertaken of aviation noise and mental health, and includes meta-analyses of studies of depression published since the WHO reviews.

Th European Environment Agency review estimates that a 10dB L_{den} increase in aircraft noise was associated with a 14% increase in risk for depression (95%CI 13-16%)[93]. The evidence for an effect of aviation noise on depression was rated as 'moderate' using the GRADE assessment, which means that the evidence is of moderate certainty, but that further research is likely to have an important impact on our confidence in the estimate of effect, and may change the estimate[18]. It was not possible to estimate effects for anxiety due to the lack of available evidence. A recent study of over 5 million people in Switzerland did not find a clear relationship between aircraft noise (L_{den}) and suicide[94]. The EEA review concluded that depression was an 'emerging' outcome to be considered in their health risk assessment of the effects of noise in Europe and recommended that depression could be included as a supplementary outcome.

In terms of where effects begin, i.e. thresholds for effects of aviation noise on mental health, there is no pooled exposure-response function available, so evidence has to be drawn from individual studies. The NORAH study around Frankfurt airport examined the health insurance data of over 655,000 individuals aged over 40 years[95]. The study found a relationship between aircraft noise and a new clinical diagnosis of depression, with odds effects starting to be observed at around 40dB-45dB $L_{Aeq,24h}$ where there was a 13% (95%CI 10-15%) increase in risk for depression. Similar estimates were found for the night-time period, with a 16% (95%CI 13-18%) increase in risk for depression at 40dB-45dB $L_{,night}$. At night, exposure below 40dB L_{night} but with at least six events per night greater than 50dB was associated with a 7% (95%CI 5-9%) increase in risk for depression. The NORAH study also estimated that the effect of aviation noise on depression was larger when individuals were exposed to aircraft noise plus one or two other transportation noise sources. For example, exposure to aircraft, road traffic, and railway noise greater than 50dB $L_{Aeq,24}$ was associated with a 42% (33-52%) increase in odds for depression.

The review for the European Environment Agency[93] also reviewed the evidence for effect on children's mental health, citing a recent meta-analysis, albeit restricted to road traffic noise exposure which showed estimated that a 10dB L_{den} increase was associated with an 11% (95%CI 4-19%) increase in odds for hyperactivity, and a 9% increase in odds for total difficulties (internalizing and externalizing combined)[96]. The EEA review did not GRADE the evidence for children's mental health[72]. A meta-analysis of studies carried out in schools around Heathrow airport found that aircraft noise was associated with small increases in hyperactivity symptoms[97]. The authors concluded that the effect was small and likely not clinically significant but could be important for public health, given exposure to aircraft noise in schools and the importance of psychological health for life chances. No effects were observed for emotional symptoms, conduct problems or Total Difficulties Score[98]. Overall, there is uncertainty in the evidence for effects of aircraft noise on children's mental health and further studies are needed.

Since the WHO review in 2018[91], and the subsequent update[92], there have been relatively few studies that have examined either wellbeing or quality of life. The 2020 review[92] concluded that there was an adverse effect of aircraft noise on wellbeing and rated the evidence as 'very low quality [99]' which means that there is little confidence in the estimated effect, and that the true estimate is likely to be substantially different from the estimated effect. Similarly, the 2020 review[92] concluded that there was no effect of aviation noise on self-reported quality of life, and also rated the evidence as 'very low quality'. The evidence for the effects of aircraft noise exposure on wellbeing and quality of life is currently limited and uncertain.

In considering noise effects on mental health, wellbeing, and quality of life, it is also necessary to consider how other factors might also be important, namely noise annoyance, noise sensitivity, and existing mental health. A systematic review found that being highly annoyed, as opposed to noise exposure per se, was associated with a 23% increase in risk for depression, a 55% increase in risk of anxiety, and a 119% increase in risk for poor mental health[31] This illustrates the importance of noise annoyance not only as a health effect in its own right, but also as a risk factor for poor mental health. Noise sensitivity, defined as a stable trait that influences an individual's reactivity to noise, may also increase effects of noise on mental health, and vice versa [30,100]. A systematic review found that both noise annoyance and noise sensitivity were associated with use of anxiety/sleep medication, with no association observed for noise exposure[101]. Further, those experiencing poor mental health may also be more sensitive to noise and environmental stressors, so might be more vulnerable [102]. A recent, novel time-series analyses of medication administration in psychiatric wards in Switzerland found that a 10 dB L_{den} military aircraft noise exposure was associated with increased on-demand use of sedatives[103,104]

Relatively few studies have examined the effect of a change in aviation noise on mental health, wellbeing, and quality of life, and overall evidence is mixed. The NORAH study around Frankfurt airport found a greater than 2dB reduction in aircraft noise after the opening of a new runway had an increase on mental quality of life but this was only found for those exposed to aircraft noise levels >=50dB $L_{Aeq,24h}$ before the change[105]. Those experiencing an increase in aircraft noise after the opening of the new runway showed a reduction in mental quality of life, but this was only found for those exposed to 40-45dB $L_{Aeq,24h}$ at baseline: this might suggest that those with lower exposure may be more likely to show reduced quality of life following a change in exposure. Effects for physical quality of life were less clear and inconsistent. An evaluation of a new noise policy around Schiphol Amsterdam airport which aimed to reduce noise by changing flight routes and night-regimes, showed no association with depressive symptoms, but nor did it demonstrate a reduction in aircraft noise levels, which would explain the null findings[106]. An evaluation of a shift in flight paths associated with the US Open Tennis Championship in New York suggested that increases in aircraft noise were associated with increased mental health emergency room visits, as well as insomnia[56].

Summary for Mental Health, Wellbeing, and Quality of Life

- Depression is an accepted public health issues for those exposed to aviation noise.
- There is good evidence that time-averaged aviation noise over the 24-hour period and night-time is associated with depression in adults, however, evidence for effects on other mental health outcomes, wellbeing, quality of life is limited and estimates uncertain.
- Studies of children suggest that aircraft noise is associated with hyperactivity in children, but further studies are needed of other child mental health outcomes
- High annoyance and noise sensitivity are also associated with mental health; and those with mental health may be more vulnerable to the effects of noise exposure.
- There are few studies of the effect of change in aviation noise on mental health, wellbeing, and quality of life.
- Guidelines that address sleep disturbance and annoyance should also protect for adult mental health.

Children's learning

Introduction

Noise as an environmental stressor can impact children's learning, in many ways including via causing communication difficulties between teachers and children, impaired attention, learned helplessness (where children might stop efforts to learn as they feel they have no control over the noise exposure), frustration, biological stress responses, noise annoyance, and as well as consequence of sleep disturbance if the child has noise exposure at home on performance the next day[107].

The European Environment Agency burden of disease assessment for noise effects in Europe in 2025 estimated that transportation noise accounted for 560,000 cases of reading difficulties for children per year [3].

Noise metrics

Studies of children's learning use traditional time-averaged metrics such as L_{day} for exposure at school, and $L_{night,outside}$ for exposure at home. The noise metrics predominantly reflect the sound levels outside these settings, but sometime concurrent internal noise is also assessed. Recent studies have examined number of event metrics (Nx) and time above metrics (Tx). A limited number of studies observing children in their classroom have examined event-based metrics such as L_{Amax}.

Measuring children's learning

A range of cognitive skills and learning outcomes have been studied in relation to aviation noise exposure. Many studies have focused on children's reading development, assessed either in by age-appropriate standardised reading tests which typically include an assessment of children's reading age, or by using Standardized Assessment Tests (SATs), which are routinely collected in schools.

Studies have also often assessed other cognitive skills, using direct tests such as working memory, short-term memory, long-term memory, and attention[107,108]. These cognitive skills, including reading comprehension are likely to be related, as cognitive skills do not exist or function in isolation[109]. Reading comprehension is a good marker of general cognitive skill and ability. Some studies have observed children in their classrooms to understand how individual aircraft noise events interfere with teaching and communication.

Evidence for health effects of aviation noise on children's learning

The WHO Environmental Noise Guidelines (ENG) 2018 undertook a systematic review of the evidence for effects of aviation noise on children's learning, however, this review[107] and a subsequent update[92] were unable to publish exposure-response functions (ERFs) for aircraft noise effects on learning due to the variety in methods and measures used across the available evidence. The WHO review included 14 studies of aircraft noise and concluded that there was moderate evidence for an effect of aviation noise on children's reading comprehension, standardized assessment tests, and short- and long-term memory. This means that the evidence is of moderate certainty, but that further research is likely to have an important impact on our confidence in the estimate of effect, and may change the estimate[18]. The updated review[92] further concluded there was very low quality evidence for an effect on student distraction, which means that that there is little confidence in the estimated effect, and that the true estimate is likely to be substantially different from the estimated effect.

The review for the European Environment Agency[93] also reviewed the evidence for effect on children's cognition, noting that whilst there was compelling evidence for an effect of transportation noise on children's learning, given the diversity of outcomes examined it was not possible to GRADE the level of evidence for the most recent studies. However, turning to individual studies, there is robust evidence that aviation noise at school affects children's learning.

The RANCH (Road traffic and Aircraft noise effects on children's Cognition & Health) study of over 2000 8-9 year old children attending schools around London Heathrow, Amsterdam Schiphol, and Madrid Barajas airports, found that aircraft noise at school was associated with poorer reading comprehension, as well as with annoyance responses[108,110]. The RANCH study took a range of socioeconomic factors that might influence noise exposure and cognitive performance into account, and the association for reading comprehension remained after further taking into account aircraft noise annoyance, other cognitive abilities, as well as co-exposure to air pollution at school[99,111]. In the UK a 5dB $L_{Aeq,16h}$ increase in aircraft noise at school was associated with a 2 month delay in reading age in the UK and a 1 month delay in the Netherlands. However, as the RANCH study was cross-sectional it was not possible to evidence whether this reading age delay may increase over the course of a child's education if they were exposed to aircraft noise for several years. A slightly lower estimate of reading age delay was found in the NORAH study of children's learning[112], where a 10dB $L_{Aeq\ 08.00\text{-}14.00h}$ increase in aircraft noise exposure at school was associated with a one month delay in reading age. A UK meta-analysis of three studies around London Heathrow airport, including the UK RANCH data estimated that a 10dB $L_{Aeq,16h}$ increase in aircraft noise at school was associated with a 40% increase in odds of scoring well below or below average on a reading test [97].

Studies also find effects for aircraft noise for L_{Amax}, number of events (Nx) and time above (Tx) noise metrics[113]. Aircraft noise exposure at home at night shows similar effects on children's learning[114], but night aircraft noise exposure does not appear to add any cognitive performance decrement to the cognitive impairment induced by daytime aircraft noise at school[114]. A study conducted in schools around Los Angeles airport found that there were a greater number of instances of teachers raising their voices and their voices being masked during aircraft noise events [115], and that L_{Aeq}, Tx and Nx metrics for both internal and external aircraft noise exposure showed similar effects.

Across the available evidence, it is suggested that time-averaged metrics are sufficient to describe the public health impacts of noise exposure at school on children's learning and remain a robust approach for quantifying these effects. The review for the European Environment Agency recommends that children's learning be included in health risk assessments as an additional outcome[93].

In terms of thresholds for effects, the RANCH study reading fell below average levels at around 55-57dB $L_{Aeq,16}$, but the exposure-response relationship between aircraft noise exposure at school which ranged from 31-77dB $L_{Aeq,16h}$ and reading comprehension was linear indicating that reducing aircraft noise exposure in schools at any level of exposure would improve children's reading.

Few studies have examined the consequences of exposure to aircraft noise at school across a child's educational years. A small-scale six year follow-up of the RANCH study UK sample found a trend between higher noise exposure at primary school and poorer reading comprehension at 15-16 years, as well as a trend between higher noise exposure at secondary school and poorer reading comprehension at 15-16 years[116]. However, this study is limited as only 45% of the UK RANCH sample were followed-up. Another study around Heathrow airport found that the effect of aircraft noise on reading comprehension did not habituate or lessen over a one-year period[117], supporting the hypothesis that children do not adapt or get used to the effects of aircraft noise at school.

A study which examined the relocation of Munich airport, found that children who were newly exposed to aircraft noise developed poorer cognition over time and that cognition improved for those who were no longer exposed to aircraft noise [118]. An American study found that performance on standardised test scores improved after insulation works within the school[113].

There is an ongoing UK study funded by Heathrow Airport and managed by the UK National Institute for Health & Care Research which is quantifying the effectiveness of insulating school classrooms on children's learning and health. This study is using standardised assessment tests to evaluate the insulation scheme over several years, as well as undertaking a feasibility study based on the RANCH methodology to collect learning and health data from children before and after the installation of insulation in their classrooms. The study is also undertaking an economic analysis of the intervention scheme on children's learning and health outcomes. Data from this study is likely to be published in the next 18-months.

Vulnerable groups

Children are thought to be more vulnerable to the effects of environmental noise on health, per se, generally because they have less developed coping strategies and are in a sensitive developmental period[27]. However, specific data identifying vulnerable sub-groups of children is lacking, but we might hypothesise that children with existing learning needs or hearing problems may be vulnerable. This is an area where further research is much needed.

Summary for Children's Learning

- Children's learning is an accepted public health issue for those exposed to aviation noise.
- There is good evidence that time-averaged aviation noise for the school setting is associated with poorer reading, memory, and standardised test scores for children.
- Evidence which suggests that noise insulation in schools improves children's learning outcomes is growing but further evidence is required, particularly quantifying the effect size and undertaking cost-benefit analysis.
- Time-averaged metrics are sufficient to describe the public health impacts of aircraft noise exposure at school on children's learning.
- Evidence for those vulnerable to the effects of aviation noise at school on children's learning is lacking.

Current guidelines

The previous sections have set out the state of the evidence for aviation noise effects on health. This section discusses approaches to setting guidelines to protect and promote public health, as well as current guidelines and the underlying epidemiological evidence that they are based upon.

Approaches to setting guidelines

Evidence for the effects of aircraft noise on health is considered in relation to ‘thresholds’ for effects, to ensure the planning system protects and promotes public health (e.g. Environmental Impact Assessments & Health Impact Assessments). Thresholds are also used to identify where mitigation is needed. Different approaches have been taken for setting and identifying thresholds, but all adopt a precautionary, public health focused approach focusing on where effects ‘begin’, as opposed to setting ‘limits’ for the highest “acceptable” level of exposure.

The WHO Night Noise Guidelines for Europe 2009 (NNG 2009)[37] introduced the use of LOAEL (Lowest Observed Adverse Effect Level) values for noise and health impact assessment. A LOAEL is the level at which the adverse effects of noise exposure on health begin to be observed in a population. The NNG 2009 set a LOAEL for night noise of 40dB $L_{night,outside}$, describing this as “a health-based limit value of the night noise guidelines necessary to protect the public, including most of the vulnerable groups such as children, the chronically ill and the elderly, from the adverse health effects of night noise.”

Some policy and guidance also set SOAEL values (Significant Observed Adverse Effect Level)[119] which reflect the level at which significant adverse effects of noise exposure on health are observed in the population. SOAEL values are usually tied to the provision of mitigation and interventions regarding noise exposure to protect public health. The identification of SOAEL values involves a judgement as to the level at which effects become ‘significant’.

In Ireland, specific SOAEL values have not been identified, however, the National Planning Framework First Revision April 2025, includes National Policy Objective 94 stating the following “**Promote the pro-active management of noise where it is likely to have significant adverse impacts on health and quality of life** and support the aims of the Environmental Noise Regulations through Strategic Noise Maps, Noise Action Plans and national planning guidance”.[120]

The identification of LOAEL and SOAEL values for a specific scheme or planning application is informed by the evidence base and available ERFs. Values are usually set for individual noise sources but not for individual health outcomes – i.e., one LOAEL is designed to protect health in general and not a specific health outcome. Today, most thresholds are based on the evidence for effects of noise on annoyance and sleep disturbance, with daytime or 24 hour exposure thresholds linked to evidence for annoyance, and night-time exposure thresholds based on evidence for subjective and/or objective sleep disturbance.

Whilst a useful framework, the use and identification of thresholds for LOAEL and SOAEL values has its challenges. The identification of a LOAEL value can be hampered by the evidence base not examining low noise exposure levels to be able to assess where effects truly 'begin'. LOAEL values can reflect where we know adverse effects occur, as opposed to where they begin. There can also be debate about how 'begin' is defined: is it where any effect is observed (e.g. any deviation in annoyance from 0%HA) or where a certain level of effect is observed (e.g. 10% HA)?

In addition, the identification of a SOAEL value is not straightforward but is a matter of interpretation of ERFs, agreement among stakeholders, political will, and the balancing of health effects versus economic benefits. ERFs rarely show a sudden or clear indication of an increase in effect (i.e., clearly indicate where effects become 'significant') and there can be debate about what 'significant' means, which can vary between stakeholders. A SOAEL value tends to be set at a high exposure level and tied to noise insulation policy, meaning that a large population who have moderate noise exposure do not get offered mitigation, and that mitigation other than the noise insulation of buildings is rarely considered, for example, the use of operational mitigation such as respite or runway and flightpath alternation. For aviation, the LOAEL and SOAEL framework, fails to identify thresholds for mitigation for those with moderate aviation noise exposure. To protect public health, it is important that this group is considered in relation to mitigation.

World Health Organization Guidelines

The WHO ENG 2018 provide recommendations for protecting human health from exposure to aircraft noise[6]:

"For average noise exposure, the GDG (Guideline Development Group) strongly recommends reducing noise levels produced by aircraft below 45dB L_{den}, as aircraft noise above this level is associated with health effects. For night noise exposure, the Guideline Development Group strongly recommends reducing noise levels produced by aircraft during night time below 40 dB L_{night}, as aircraft noise above this level is associated with adverse effects on sleep."

These levels represent those at which 10% of the population will be 'highly annoyed' for L_{den} and at which 11% of the population would report being 'highly sleep disturbed' (self-reported sleep disturbance) for L_{night}. The WHO ENG 2018 night-time recommendation matches that proposed in the WHO NNG 2009[37].

The WHO ENG 2018 identified the 'lowest' threshold across the health outcomes examined, therefore, adherence to the guidelines should protect across a range of health outcomes in the population and not just protect from annoyance and sleep disturbance. The European Environment Agency also highlighted that annoyance and sleep disturbance are both also a pathway to cardiometabolic diseases[27], which further supports the idea that addressing annoyance and sleep disturbance can addresses other health outcomes in the local population.

Whilst there has been debate about the WHO guideline levels[121,122], and concerns that the Guidelines were not informed by a socioeconomic assessment of the impact of setting these levels economically on the aviation industry and society, the guidelines follow an established methodology used by the WHO across a their development of guidelines, and is not specific to noise exposure and health. A recent addition to the European Noise Directive requires that member countries estimate the WHO ERF for % highly annoyed, % highly sleep disturbed and ischaemic heart disease to report the harmful effects of environmental noise for road noise, railway noise, and aircraft noise[11].

The WHO ENG 2018 further suggested that

"*The WHO guideline values are public health-oriented recommendations, based on scientific evidence on health effects and on an assessment of achievable noise levels. They are strongly recommended and as such should serve as the basis for a policy-making process in which policy options are quantified and discussed. It should be recognized that in that process additional considerations of costs, feasibility, values and preferences should also feature in decision-making when choosing reference values such as noise limits for a possible standard or legislation." (Page 29 of the WHO ENG 2018.)*

Somewhat confusingly, the WHO ENG state that the guideline levels are not LOAEL values, differing from the WHO NNG which were LOAEL values aiming to identify thresholds for no effect (p20). This leads to uncertainty as to how to treat the WHO ENG 2018 values in impact assessment. It could be argued that a LOAEL would be lower than the ENG 2018 values, as these were set based on the presence of adverse effects, indicating where 10% of the population are annoyed and 11% of the population are sleep disturbed, and do not indicate where effects begin.

Night protection zone approach

Basner et al proposed a health protection scheme to manage the risk of sleep disturbances associated with aircraft noise for Leipzig/Halle airport in Germany[42], which has become very influential in environmental and health impact assessment. Leipzig/Halle airport was undergoing operational changes which included turning and extending a runway; introducing a parallel runway system with simultaneous take-offs and landings; and a significant increase in night-flights associated with the opening of an international freight hub. The night protection zone was determined by the overlay of a continuous sound level value for the night-time period from 10:00 p.m. to 6:00 a.m. and a frequency event-related maximum level criterion[123]. It sets out that on average there should be less than one additional EEG awakening induced by aircraft noise per night. This is an annualised metric, so there can be more than one additional EEG awakening per night if there are other nights when no additional EEG awakenings per night occur. A recent publication[123] suggests that the one additional awakening criteria is a SOAEL value, as it is described as identifying where 'Building restrictions and the eligibility for reimbursement of structural noise abatement measures are legal consequences for properties located in the protection zone.". This aligns one additional awakening with the use of SOAEL values to identify where mitigation should be offered to residents.

Airports can plot 'awakening' contours for the local population, showing where there would be one or more additional awakening due to aircraft noise or how the awakening contours would change with operational changes to the airport. Awakening contours form an important additional tool for estimating and managing the effects of aviation night-noise. They take into account the noise level of individual aircraft noise events in the night-time period, taking consideration of health effects beyond time-average[27] noise metrics which may not well represent exposure in terms of the noise level, distribution, and fleet mix of aircraft within the night-time period and variation by aircraft type[43]. Awakening contours are probably best aligned with identifying those most impacted by aviation noise at night for mitigation schemes, with the evidence suggesting that they do not identify additional health effects beyond those identified by other means or metrics[43]. Recent analysis led the UK CAA to concluded that "The analysis found that $L_{Aeq,8h}$ and L_{night} do correlate with the number of additional aircraft noise-induced awakenings arising from individual aircraft events at night and the self-reported sleep disturbance results found in the SoNA 2014 survey. Consequently, the concerns that are expressed that averaging the night-time noise exposure does not properly reflect the impact of individual aircraft noise events may be unfounded."[43]

Producing awakening contours to estimate the impact of an airspace or operational change on sleep disturbance in the local population may not be straightforward. Assumptions may have to be made about the future airport fleet and operations, as well as the variability of flight paths. These assumptions add uncertainty to the production of awakening contours. The use of time-weighted noise metrics is more straightforward, removing this uncertainty.

Protecting public health

Interventions to protect public health in the local population are a key consideration for airport development. Reviewing the evidence base as a whole across the range of outcomes, effects of aviation noise on health become detectable at around 40-45dB L_{night}/L_{den}. Exposures in the early to mid 50dB range are associated with considerable prevalence of effects in the population, for example 20% reporting annoyance or subjective sleep disturbance. The evidence base also suggests that these levels of exposure are associated with increased risk for depression, cardiovascular and metabolic disease, and children's learning. Exposures greater than 55dB are accepted as indicating adverse health effects[3], with mitigation, particularly insulation of homes being offered to those with the highest levels of aviation noise exposure (e.g. 63dB and higher). Whilst the focus on thresholds for effects is important for quantifying the total burden of disease from aviation noise in a population, it should not detract from mitigation efforts for those where exposure is contributing to considerable prevalence of health effects in the local population: that is mitigation for those exposed in the 50-60dB range.

Conclusion

Aviation noise is a systemic health stressor that disrupts multiple bodily systems[3]. There is evidence that aviation noise is associated with noise annoyance, subjective and objective sleep disturbance, a range of cardiovascular diseases, Type 2 diabetes, depression, and impairment of children's cognitive skills. There is uncertainty in the magnitude of the effect for some outcomes, e.g. cardiovascular diseases, but this is not an indication that aviation is not associated with adverse effects, but an indication that further studies are needed to be able to estimate the effect with greater precision. Mitigation efforts should not be restricted to those with the highest levels of aircraft noise exposure (~≥60dB $L_{Aeq,16h}$/~≥55dB $L_{Aeq,8h}$), but consideration should be given to protecting public health through measures and interventions that reduce noise exposure in the 50-60dB $L_{Aeq,16h}$ /45-55dB $L_{Aeq,8h}$ range. Evidence supporting the use of insulation schemes for those exposed to the highest levels of aviation noise is emerging.

References

1. Guski R. Personal and social variables as co-determinants of noise annoyance. *Noise Health* 1999; **1**(3): 45-56.

2. Guski R, Schreckenberg D, Schuemer R. WHO Environmental Noise Guidelines for the European Region: A systematic review on environmental noise and annoyance. *Int J Environ Res Public Health* 2017; **14**(12): 1539.

3. European Environment Agency. Environmental Noise in Europe, 2025.

4. Munzel T, Sorensen M, Schmidt F, et al. The Adverse Effects of Environmental Noise Exposure on Oxidative Stress and Cardiovascular Risk. *Antioxidants & redox signaling* 2018; **28**(9): 873-908.

5. Munzel T, Sorensen M, Gori T, et al. Environmental stressors and cardio-metabolic disease: part II-mechanistic insights. *Eur Heart J* 2017; **38**(8): 557-64.

6. World Health Organization. The World Health Organization Guidelines for Environmental Noise Exposure for the European Region. Copenhagen: Denmark: World Health Organization Europe, 2018.

7. Civil Aviation Authority. CAP1506: Survey of Noise Attitudes 2014. London; United Kingdom: Civil Aviation Authority, 2021.

8. City St George's University of London. https://www.sgul.ac.uk/about/our-institutes/population-health/projects/aviation-night-noise-effects-study. 2025 (accessed 26 May 2025.

9. ISO/IEC. ISO/TS 15666:2021 Acoustics — Assessment of noise annoyance by means of social and socio-acoustic surveys, 2021.

10. ISO/TS15666. Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys. Geneva: Reference No. ISO/TC 43/SC 1 N 1313 2003.: International Organization for Standardization, 2003.

11. EU Directive. 2020/367 of 4 March 2020 amending Annex III to Directive 2002/49/EC of the European Parliament and of the Council as regards the establishment of assessment methods for harmful effects of environmental noise, 2020.

12. Clark C, Gjestland T, Lavia L, Notley H, Michaud D, Morinaga M. Assessing community noise annoyance: A review of two decades of the international technical specification ISO/TS 15666:2003. *The Journal of the Acoustical Society of America* 2021; **150**(5): 3362-73.

13. ICAO. ICAO CAEP/12 White Paper: Non-acoustic factors in community annoyance due to aviation noise, 2024.

14. Vader R. Noise Annoyance Mitigation at Airports by Non-Acoustic Measures.

Amsterdam, The Netherlands,: D/R&D 07/026; LVNL, 2007.

15. Fenech B, Lavia L, Rodgers G, Notley H. Development of a new ISO Technical Specification on non-acoustic factors to improve the interpretation of socio-acoustic surveys. Paper presented at the 13th ICBEN Congress on Noise as a Public Health Problem. 14-17 June, Stockholm; 2021.

16. Notley H, Grimwood C, Raw G, et al. National Noise Attitude Survey 2012 (NNAS2012): Summary Report. London: DEFRA, 2014.

17. ANIMA. D2.4 Recommendations on annoyance mitigation and implications for communication and engagement: Aviation Noise Impact Management through novel Approaches, 2019.

18. Guyatt GH, Oxman AD, Vist G, et al. Rating quality of evidence and strength of recommendations GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. *Br Med J* 2008; **336**: 924-6.

19. Brown AL, van Kamp I. WHO Environmental Noise Guidelines for the European Region: A systematic review of transport noise interventions and their health effects. *Int J Environ Res Public Health* 2017; **14**(8): 873.

20. Brink M, Wirth KE, Schierz C, Thomann G, Bauer G. Annoyance responses to stable and changing aircraft noise exposure. *J Acoust Soc Am* 2008; **124**(5): 2930-41.

21. Fidell S, Silvati L, Haboly E. Social survey of community response to a step change in aircraft noise exposure. *J Acoust Soc Am* 2002; **111**(1 Pt 1): 200-9.

22. Nguyen TL, Nguyen TL, Morinaga M, et al. Community response to a step change in the aircraft noise exposure around Hanoi Noi Bai International Airport. *J Acoust Soc Am* 2018; **143**(5): 2901.

23. Quehl J, Muller U, Mendolia F. Short-term annoyance from nocturnal aircraft noise exposure: results of the NORAH and STRAIN sleep studies. *Int Arch Occup Environ Health* 2017; **90**(8): 765-78.

24. Breugelmans O, Houthuijs D, van Kamp I, Stellato R, van Wiechen C, Doornbos G. Longitudinal effects of a sudden change in aircraft noise exposure on annoyance and sleep disturbance around Amsterdam Airport. International Congress on Acoustics. Madrid; 2007.

25. Civil Aviation Authority. CAP2250: Survey of Noise Attitudes 2014: Aircraft Noise and Annoyance, Further Analysis. London, United Kingrom, 2022.

26. Civil Aviation Authority. 2025. https://www.caa.co.uk/passengers-and-public/environment/noise/aviation-noise-attitudes-survey/ (accessed 13 June 2025.

27. European Environment Agency. Environmental Noise in Europe 2020. Luxembourg: Publications of the European Union, 2020.

28. Henry JA, Theodoroff SM, Edmonds C, et al. Sound Tolerance Conditions (Hyperacusis, Misophonia, Noise Sensitivity, and Phonophobia): Definitions and Clinical Management. *Am J Audiol* 2022; **31**(3): 513-27.

29. Stansfeld SA. Noise, noise sensitivity and psychiatric disorder: epidemiological and psychophysiological studies. *Psychol Med* 1992; **Suppl 22**: 1-44.

30. Cerletti P, Eze IC, Schaffner E, et al. The independent association of source-specific transportation noise exposure, noise annoyance and noise sensitivity with health-related quality of life. *Environment international* 2020; **143**: 105960.

31. Gong X, Fenech B, Blackmore C, et al. Association between noise annoyance and mental health outcomes: A systematic review and meta-analysis. *Int J Environ Res Public Health* 2022; **19**(5): 2696.

32. Heathrow Airport Limited. Residential Insulation Scheme FAQs. 2026. https://www.heathrow.com/company/local-community/noise/what-you-can-do/quieter-neighbourhood-support/frequently-asked-questions (accessed 04 March 2026.

33. Clark C, Wahlich C, Aksoy C, Monaghan R, Porter N, Norman R. Preliminary insights from a pilot of a longitudinal study on the impact of Heathrow's Noise Insulation Scheme on quality of life and health Internoise 2025. Sao Paulo, Brazil; 2025.

34. Basner M, Smith MG, Cordoza M, et al. Efficacy of pink noise and earplugs for mitigating the effects of intermittent environmental noise exposure on sleep. *Sleep* 2026.

35. Logika Group. ANCA Framework 2024 Recent Trends in Airport Noise Insulation and Compensation Programmes in Europe, 2026.

36. Watson NF, Badr MS, Belenky G, et al. Joint Consensus Statement of the American Academy of Sleep Medicine and Sleep Research Society on the Recommended Amount of Sleep for a Healthy Adult: Methodology and Discussion. *J Clin Sleep Med* 2015; **11**(8): 931-52.

37. World Health Organization. Night Noise Guidelines for Europe. Cophenhagen, Denmark: World Health Organization Europe, 2009.

38. Rundo JV, Downey R, 3rd. Polysomnography. *Handb Clin Neurol* 2019; **160**: 381-92.

39. Basner M, Barnett I, Carlin M, et al. Effects of Aircraft Noise on Sleep: Federal Aviation Administration National Sleep Study Protocol. *Int J Environ Res Public Health* 2023; **20**(21).

40. Smith MG, Rocha S, Witte M, Basner M. On the feasibility of measuring physiologic and self-reported sleep disturbance by aircraft noise on a national scale: A pilot study around Atlanta airport. *Sci Total Environ* 2020; **718**: 137368.

41. Michaud DS, Keith SE, Guay M, Voicescu S, Denning A, McNamee JP. Sleep actigraphy time-synchronized with wind turbine output. *Sleep* 2021.

42. Basner M, Samel A, Isermann U. Aircraft noise effect on sleep: application of the results of a large polysomnographic field study. *The Journal of the Acoustical Society of America* 2006; **119**(5): 2772-84.

43. Civil Aviation Authority. CAP2251: Survey of Noise Attitudes 2014: Aircraft noise and sleep disturbance, further analysis. Crawley, West Sussex, 2022.

44. Basner M, McGuire S. WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Effects on Sleep. *Int J Environ Res Public Health* 2018; **15**(3): 519.

45. NORAH Knowledge No 5. NORAH Noise Impact Study Sleep Study: effects of aircraft noise on sleep – Objective & Method.

46. Basner M, Müller U, Elmenhorst EM. Single and combined effects of air, road, and rail traffic noise on sleep and recuperation. *Sleep* 2011; **34**: 11-23.

47. Röösli M, Brink M, Rudzik F, et al. Associations of Various Nighttime Noise Exposure Indicators with Objective Sleep Efficiency and Self-Reported Sleep Quality: A Field Study. *Int J Environ Res Public Health* 2019; **16**(20).

48. NORAH Knowledge No 10. NORAH Noise Impact Study: Aircraft noise and nocturnal sleep.

49. Department for Transport. The ANNE (Aviation Night Noise Effects) Study. 2025. https://www.sgul.ac.uk/about/our-institutes/population-health/projects/aviation-night-noise-effects-study (accessed 10 June 2025.

50. Smith MG, Cordoza M, Basner M. Environmental Noise and Effects on Sleep: An Update to the WHO Systematic Review and Meta-Analysis. *Environ Health Perspect* 2022; **130**(7): 76001.

51. Civil Aviation Authority. CAP 2161: Survey of Noise Attitudes 2014: Aircraft noise and sleep disturbance. Crawley: West Sussex, 2021.

52. ISO/TS15666:2003. Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys. Geneva; Switzerland: International Organization for Standardization, 2003.

53. Nguyen LT, Nguyen TL, Yano T, et al. Social surveys around Noi Bai airport before and after the opening of a new terminal building. *44th International Congress and Exposition on Noise Control Engineering, InterNoise San Francisco, CA, Aug 9-12, 2015* 2015.

54. Yano T, Nguyen TL, Nguyen TL, et al. Community response to a step change in aircraft noise exposure: The first socio-acoustic survey around Noi Bai airport in Hanoi. *International Congress on Sound and Vibration (ICSV 22), Florence, Italy, July 12-16, 2015* 2015.

55. Nguyen T, Trieu BL, Nguyen TL, et al. Models of Aviation Noise Impact in the Context of Operation Decrease at Tan Son Nhat Airport. *Int J Environ Res Public Health* 2023; **20**(8).

56. Wang SS, Glied S, Williams S, Will B, Muennig PA. Impact of aeroplane noise on mental and physical health: a quasi-experimental analysis. *BMJ Open* 2022; **12**(5): e057209.

57. McGuire S, Muller U, Elmenhorst EM, Basner M. Inter-individual Differences in the Effects of Aircraft Noise on Sleep Fragmentation. *Sleep* 2016; **39**(5): 1107-10.

58. Schmidt F, Kolle K, Kreuder K, et al. Nighttime aircraft noise impairs endothelial function and increases blood pressure in patients with or at high risk for coronary artery disease. *Clin Res Cardiol* 2015; **104**(1): 23-30.

59. WHO. Night Noise Guidelines for Europe. Cophenhagen, Denmark: World Health Organization Europe, 2009.

60. Basner M, Witte M, McGuire S. Aircraft Noise Effects on Sleep—Results of a Pilot Study Near Philadelphia International Airport. *Int J Environ Res Public Health* 2019; **16**(17): 3178.

61. Mensah GA, Fuster V, Murray CJL, Roth GA. Global Burden of Cardiovascular Diseases and Risks, 1990-2022. *J Am Coll Cardiol* 2023; **82**(25): 2350-473.

62. GBD 2021 Diabetes Collaborators. Global, regional, and national burden of diabetes from 1990 to 2021, with projections of prevalence to 2050: a systematic analysis for the Global Burden of Disease Study 2021. *Lancet* 2023; **402**(10397): 203-34.

63. Landrigan PJ, Fuller R, Acosta NJR, et al. The Lancet Commission on pollution and health. *Lancet* 2018; **391**(10119): 462-512.

64. Osborne MT, Radfar A, Hassan MZO, et al. A neurobiological mechanism linking transportation noise to cardiovascular disease in humans. *Eur Heart J* 2020; **41**(6): 772-82.

65. Marques JG, Kuntic M, Krishnankutty R, et al. Short-term aircraft noise stress induces a fundamental metabolic shift in heart proteome and metabolome that bears the hallmarks of cardiovascular disease. *Sci Total Environ* 2025; **979**: 179484.

66. Münzel T, Daiber A, Steven S, et al. Effects of noise on vascular function, oxidative stress, and inflammation: mechanistic insight from studies in mice. *Eur Heart J* 2017; **38**(37): 2838-49.

67. Steven S, Frenis K, Kalinovic S, et al. Exacerbation of adverse cardiovascular effects of aircraft noise in an animal model of arterial hypertension. *Redox Biol* 2020: 101515.

68. Eminson K, Cai YS, Chen Y, et al. Does air pollution confound associations

between environmental noise and cardiovascular outcomes? - A systematic review. *Environ Res* 2023; **232**: 116075.

69. Foraster M, Eze IC, Vienneau D, et al. Long-term transportation noise annoyance is associated with subsequent lower levels of physical activity. *Environ Int* 2016; **91**: 341-9.

70. Van Kempen E, Casas M, Pershagen G, Foraster M. WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Cardiovascular and Metabolic Effects: A Summary. *Int J Environ Res Public Health* 2018; **15**(2): 379.

71. Vienneau D, Wicki B, Flückiger B, Schäffer B, Wunderli JM, Röösli M. Long-term exposure to transportation noise and diabetes mellitus mortality: a national cohort study and updated meta-analysis. *Environ Health* 2024; **23**(1): 46.

72. Engelmann N, Blanes Guardia N, Fons-Esteve J, Viennau D, Peris E, Roosli M. TC HE Report 2023/11: Version 3; Environmental noise health risk assessment: methodology for assessing health risks using data reported under the Environmental Noise Directive, 2025.

73. Sivakumaran K, Ritonja JA, Waseem H, et al. Impact of Noise Exposure on Risk of Developing Stress-Related Health Effects Related to the Cardiovascular System: A Systematic Review and Meta-Analysis. *Noise Health* 2022; **24**(114): 107-29.

74. Cai Y, Ramakrishnan R, Rahimi K. Long-term exposure to traffic noise and mortality: A systematic review and meta-analysis of epidemiological evidence between 2000 and 2020. *Environ Pollut* 2021; **269**: 116222.

75. Grady ST, Hart JE, Laden F, et al. Associations between long-term aircraft noise exposure, cardiovascular disease, and mortality in US cohorts of female nurses. *Environ Epidemiol* 2023; **7**(4): e259.

76. Münzel T, Kuntic M, Daiber A, Sørensen M. Transportation noise and the cardiometabolic risk. *Atherosclerosis* 2025; **403**: 119148.

77. Thacher JD, Poulsen AH, Hvidtfeldt UA, et al. Long-Term Exposure to Transportation Noise and Risk for Type 2 Diabetes in a Nationwide Cohort Study from Denmark. *Environ Health Perspect* 2021; **129**(12): 127003.

78. Saucy A, Schaffer B, Tangermann L, Vienneau D, Wunderli JM, Roosli M. Does night-time aircraft noise trigger mortality? A case-crossover study on 24 886 cardiovascular deaths. *Eur Heart J* 2021; **42**(8): 835-43.

79. Gong X, Itzkowitz N, Jephcote C, et al. Impact of short-term aircraft noise on cardiovascular disease risk in the area surrounding London Heathrow airport: the RISTANCO epidemiological study. *Public Health Res (Southampt)* 2024; **12**(13): 1-58.

80. Cantuaria ML, Waldorff FB, Wermuth L, et al. Residential exposure to

transportation noise in Denmark and incidence of dementia: national cohort study. *BMJ* 2021: n1954.

81. Haralabidis AS, Dimakopoulou K, Vigna-Taglianti F, et al. Acute effects of night-time noise exposure on blood pressure in populations living near airports. *Eur Heart J* 2008; **29**(5): 658-64.

82. Vienneau D, Schindler C, Perez L, Probst-Hensch N, Roosli M. The relationship between transportation noise exposure and ischemic heart disease: a meta-analysis. *Environ Res* 2015; **138**: 372-80.

83. NORAH Knowledge No 11. NORAH Knowledge No 11. NORAH Noise Impact Study Blood Pressure Study: effects of aircraft noise on blood pressure – Results.

84. Chaturvedi N. Ethnic differences in cardiovascular disease. *Heart* 2003; **89**(6): 681-6.

85. Casey JA, Morello-Frosch R, Mennitt DJ, Fristrup K, Ogburn EL, James P. Race/Ethnicity, Socioeconomic Status, Residential Segregation, and Spatial Variation in Noise Exposure in the Contiguous United States. *Environ Health Perspect* 2017; **125**(7): 077017.

86. Tonne C, Milà C, Fecht D, et al. Socioeconomic and ethnic inequalities in exposure to air and noise pollution in London. *Environ Int* 2018; **115**: 170-9.

87. World Health Organization. Mental Health. 2022. https://www.who.int/news-room/fact-sheets/detail/mental-health-strengthening-our-response (accessed 19 July 2025.

88. Goodman RJ. The strengths and difficulties questionnaire. *J Child Psychol Psych* 1997; **38**: 581-86.

89. ONS. Measuring what matters: National Statistician's Reflections on the National Debate on Measuring National Well-being. Cardiff, United Kingdom: Office for National Statistics, 2011.

90. WHO. The World Health Organization Quality of Life assessment (WHOQOL): position paper from the World Health Organization. *Soc Sci Med* 1995; **41**(10): 1403-9.

91. Clark C, Paunović K. WHO Environmental Noise Guidelines for the European Region: Systematic review of the evidence on the effects of environmental noise on quality of life, wellbeing and mental health. *Int J Environ Res Public Health* 2018; **15**(11): 2400.

92. Clark C, Crumpler C, Notley H. Evidence for environmental noise effects on health for the United Kingdom policy context: A systematic review of the effects of environmental noise on mental health, wellbeing, quality of life, cancer, dementia, birth, reproductive outcomes, and cognition. *Int J Environ Res Public Health* 2020; **17**(393).

93. Engelmann N, Blanes Guardia N, Fons Esteve J, Vienneau D, Roosli M, Peris E. ETC HE Report 2023/11: Environmental noise health risk assessment: methodology for assessing health risks using data reported under the Environmental Noise Directive, 2024.

94. Wicki B, Schäffer B, Wunderli JM, et al. Suicide and Transportation Noise: A Prospective Cohort Study from Switzerland. *Environ Health Perspect* 2023; **131**(3): 37013.

95. Seidler A, Hegewald J, Seidler AL, et al. Association between aircraft, road and railway traffic noise and depression in a large case-control study based on secondary data. *Environ Res* 2017; **152**: 263-71.

96. Schubert M, Hegewald J, Freiberg A, et al. Behavioral and Emotional Disorders and Transportation Noise among Children and Adolescents: A Systematic Review and Meta-Analysis. *Int J Environ Res Public Health* 2019; **16**(18).

97. Clark C, Head J, van Kamp I, van Kempen E, Haines M, Stansfeld S. A meta-analysis of the association of aircraft noise at school on children's reading comprehension and psychological health for use in Health Impact Assessment. *J Environ Psychol* 2021: 101646.

98. Clark C, Head J, van Kamp I, van Kempen E, Haines M, Stansfeld S. A meta-analysis of the association of aircraft noise at school on children's reading comprehension and psychological health for use in Health Impact Assessment. *J Environ Psychol* Under review.

99. Clark C, Crombie R, Head J, van Kamp I, van Kempen E, Stansfeld SA. Does traffic-related air pollution explain associations of aircraft and road traffic noise exposure on children's health and cognition? A secondary analysis of the United Kingdom sample from the RANCH project. *Am J Epidemiol* 2012; **176**(4): 327-37.

100. Stansfeld S, Clark C, Smuk M, Gallacher J, Babisch W. Road traffic noise, noise sensitivity, noise annoyance, psychological and physical health and mortality *Environmental Health* 2021; **20**: 32.

101. Baudin C, Lefèvre M, Babisch W, et al. The role of aircraft noise annoyance and noise sensitivity in the association between aircraft noise levels and medication use: results of a pooled-analysis from seven European countries. *BMC Public Health* 2021; **21**(1): 300.

102. Nordin S, Ljungberg JK, Claeson AS, Neely G. Stress and odor sensitivity in persons with noise sensitivity. *Noise Health* 2013; **15**(64): 173-7.

103. Wicki B, Vienneau D, Schäffer B, et al. Acute effects of military aircraft noise on sedative and analgesic drug administrations in psychiatric patients: A case-time series analysis. *Environ Int* 2024; **185**: 108501.

104. Wicki B, Vienneau D, Schäffer B, Müller TJ, Pervilhac C, Röösli M. Military aircraft noise and drug administrations in psychiatric patients: Follow-up and in-depth case-time series analysis. *Environ Epidemiol* 2025; **9**(3): e390.

105.Schreckenberg D, Faulbaum F, Guski R, et al. Wirkungen von Verkehrslärm auf die Belästigung und Lebensqualität (The impact of transportation noise on annoyance and health-related quality of life). Kelsterbach: Umwelthaus gGmbH, 2015.

106.Li L, Carrino L, Reinhard E, et al. Aircraft noise control policy and mental health: a natural experiment based on the Longitudinal Aging Study Amsterdam (LASA). *J Epidemiol Community Health* 2021; **75**(5): 458-63.

107.Clark C, Paunović K. WHO Environmental Noise Guidelines for the European Region: A systematic review on environmental noise and cognition. *Int J Environ Res Public Health* 2018; **15**: 285.

108.Stansfeld SA, Berglund B, Clark C, et al. Aircraft and road traffic noise and children's cognition and health: a cross-national study. *Lancet* 2005; **365**(9475): 1942-9.

109.Sorqvist P. On interpretation and task selection in studies on the effects of noise on cognitive performance. *Front Psychol* 2014; **5**: 1249.

110.Clark C, Martin R, van Kempen E, et al. Exposure-effect relations between aircraft and road traffic noise exposure at school and reading comprehension: the RANCH project. *Am J Epidemiol* 2006; **163**(1): 27-37.

111.Clark C, Martin R, van Kempen E, et al. Exposure-effect relations between aircraft and road traffic noise exposure at school and reading comprehension - The RANCH project. *Am J Epidemiol* 2006; **163**(1): 27-37.

112.Klatte M, Spilski J, Mayerl J, U. M, T. L, Bergström K. Effects of aircraft noise on reading and quality of life in primary school children in Germany: results from the NORAH study. *Environ Behav* 2016; **49**: 390-424.

113.Sharp B, Connor TL, McLaughlin D, Clark C, Stansfeld SA, Hervey J. Assessing aircraft noise conditions affecting student learning: Transportation Research Board of the National Academies, 2014.

114.Stansfeld SA, Hygge S, Clark C, Alfred T. Night time aircraft noise exposure and children's cognitive performance. *Noise Health* 2010; **12**(49): 255-62.

115.Eagan ME, Nicholas B, McIntosh S, Clark C, Evans G. Assessing aircraft noise conditions affecting student learning - Case Studies, 2017.

116.Clark C, Head J, Stansfeld SA. Longitudinal effects of aircraft noise exposure on children's health and cognition: A six-year follow-up of the UK RANCH cohort. *J Environ Psychol* 2013; **35**: 1-9.

117.Haines MM, Stansfeld SA, Job RF, Berglund B, Head J. A follow-up study of effects of chronic aircraft noise exposure on child stress responses and cognition. *Int J Epidemiol* 2001; **30**(4): 839-45.

118.Hygge S, Evans GW, Bullinger M. A prospective study of some effects of aircraft noise on cognitive performance in schoolchildren. *Psychological* *science* 2002; **13**(5): 469-74.

119.Department for Environment Food and Rural Affairs. Noise Policy Statement for England. London United Kingdom, 2010.

120.Government of Ireland. National Planning Framework First Revision April 2025. 2025.

121.Guski R, Schreckenberg D, Schuemer R, Brink M, Stansfeld SA. Comment on Gjestland, T. A Systematic Review of the Basis for WHO's New Recommendation for Limiting Aircraft Noise Annoyance. Int. J. Env. Res. Pub. Health 2018, 15, 2717. *Int J Environ Res Public Health* 2019; **16**(7).

122.Gjestland T. A systematic review of the basis for WHO's new recommendation for limiting aircraft noise annoyance. *Int J Environ Res Public Health* 2018; **15**: 2717.

123.Kuhlmann J, Bilik BA, Belke C, et al. Vergleich vorhandener Verfahren zur Beurteilung von ächtlichem Fluglärm und für Entscheidungen über baulichen Schallschutz für Schlafräume, 2025.