

# Aircraft Noise and Sleep Disturbance: An update (2014-2022)

**CAP 2370**



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## CHAPTER 1

# Introduction

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In January 2013, the Environmental Research and Consultancy Department (ERCD) of the Civil Aviation Authority (CAA) published ERCD Report 1208, entitled 'Aircraft Noise, Sleep Disturbance and Health Effects: A Review'. This report provided an overview of the main findings within environmental noise at night and health research from the 1970s to 2013 and included the effects of sleep disturbance due to aircraft noise. The cost-benefit analysis of night flights was also discussed in terms of previous methodology and proposals for future evaluation of the aircraft movements at night were suggested.

This report covered the main effects of nocturnal environmental noise, such as cardiovascular disease, sleep disturbance and next day effects, and the impacts on children. This was followed in 2014 by CAP1164: Aircraft noise, sleep disturbance and health effects, which was an overview of developments since the publication of ERCD Report 1208, in the research field of aircraft noise, sleep disturbance and health effects.

The aim of this report is to provide an update of the main findings on aircraft noise and sleep disturbance between 2014 – 2022. Such research findings include those from the NORAH study, the updated World Health Organisation (WHO) Environmental Noise Guidelines for the European Region (2018), the DEBATS study, the Survey of Noise Attitudes (SoNA) study, and other relevant publications.

This report will be presented in subject area by chapter and concludes with a summary and references.

## CHAPTER 2

# Nocturnal Aircraft Noise and Cardiovascular Disease

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Much of the focus of the effects of aircraft noise at night has been on the relationship between night noise, sleep disturbance and cardiovascular effects. This chapter includes the main findings in this area since 2014.

A decrease in the quality of sleep, coupled with interruptions from noise are important factors in the relationship between annoyance and sleep disturbance and the development of noise-induced cardiovascular disease. During sleep, physiological responses occur even if the sleeper is not aware of them, meaning habituation to intermittent noise such as that from aircraft, is not possible. There are individual differences in terms of responses to noise at night from aircraft, which cannot be explained by non-acoustic factors such as age or gender. Due to these individual differences, it is important to identify those at higher risk for noise induced sleep disturbance (McGuire et al, 2016).

The consequences of interrupted sleep from transport noise can be classified as immediate reactions, short-term reactions, and long-term consequences (Benz et al, 2020).

- **Immediate reactions to nocturnal noise:** Acute noise exposure affects the function of multiple organs and systems, including an increase in blood pressure and heart rate. These reactions are most likely induced by the release of stress hormones, such as adrenaline and noradrenaline. Stress reactions such as these occur even when not perceived, such as during sleep. As a result of the physiological changes described, reactions in sleep can ensue, such as changes from a deeper to a lighter sleep stage, awakenings, body movements, resulting in an increase in total wake time, a reduction of the time spent in deep sleep, and more general sleep loss.
- **Short-term reactions to night noise:** Due to the decrease in overall sleep time, next day effects include sleepiness and a decrease in cognitive performance. There may also be an impact on mood and wellbeing.
- **Long-term reactions:** Chronic sleep loss and recurring interruptions of sleep are a major risk factor for cardiovascular and metabolic diseases. The relationship between the immediate and long-term effects of noise is not completely clear, yet, as mediators such as noise annoyance seem to play a relevant role for long-term health effects. Nocturnal aircraft noise exposure has also been found to increase the risk of developing hypertension via a direct effect on blood pressure as well as via a mediated effect because of chronic sleep disturbance.

Basner published a review in the Lancet in 2014, which looked at auditory and non-auditory aspects of noise with a focus on potential mitigation measures and noise

prevention methods. The review summarised the knowledge on auditory effects of noise such as occupational noise-induced hearing loss, tinnitus and age-related hearing loss. The non-auditory part of the review discussed the effects of environmental noise exposure on annoyance, cardiovascular disease, cognitive impairment in children and sleep disturbance. The review summarised findings from the World Health Organisation (WHO), which estimated that in western European countries at least 1 million healthy life years (Disability Adjusted Life Years, or DALYs) are lost every year due to environmental noise, with most being attributed to sleep disturbance and annoyance.

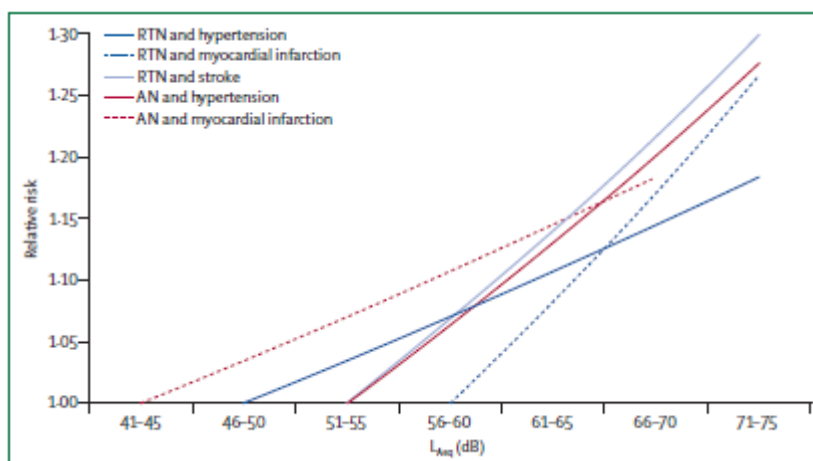
In terms of cardiovascular disease, the review discussed chronic and acute effects of environmental noise exposure, with chronic exposure contributing to hypertension, ischaemic heart disease and stroke, and acute exposure being associated with arousals of the autonomic nervous system and endocrine system. The general stress model is suggested as a pathway for reactions such as increases in blood pressure and the release of stress hormones, with mechanisms such as stress reactions due to discomfort (indirect) and non-conscious physiological stress from interactions between the central auditory system and other regions of the central nervous system (direct). It is suggested that the direct pathway could be the more likely pathway during sleep.

With chronic noise exposure, metabolism and the cardiovascular system are affected, with increases in cardiovascular risk factors such as blood pressure, blood lipid levels, viscosity, and blood glucose concentrations. The authors report that these changes increase the risk of hypertension, arteriosclerosis<sup>1</sup> and are linked to myocardial infarction and stroke. It is suggested that due to the different acoustic characteristics for different noise sources, there is a need for different exposure-response curves for the different noise sources.

Meta-analyses were previously conducted for road and aircraft noise, and for the relationship with cardiovascular disease such as ischaemic heart disease (including myocardial infarction) and hypertension. The studies suggested increases in risk of ischaemic heart disease of between 7% and 17% per 10 dB increase in equivalent noise level  $L_{Aeq}$ . The results were adjusted for known risk factors such as age, sex, socioeconomic status, smoking, body-mass index, and others. The researchers identified sex and age as effect modifiers. The dose-response curves for the meta-analyses are shown in Figure 1.

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<sup>1</sup> Arteriosclerosis refers to hardening and narrowing of the arteries caused by cholesterol plaques lining the artery over time.



**Figure 1:** Exposure–response curves for road and aircraft noise and cardiovascular endpoints. Road Traffic Noise (RTN) and hypertension (24 studies, noise indicator  $L_{Aeq,16h}$ ); RTN and myocardial infarction (MI) (five studies, noise indicator  $L_{Aeq,16h}$ ); RTN and stroke (one study, noise indicator  $L_{dn}$ ); Aircraft Noise (AN) and hypertension (five studies, noise indicator  $L_{dn}$ ); and AN and MI (one study, noise indicator  $L_{dn}$ ).

Münzel et al also published a review in 2014 on the cardiovascular effects of environmental noise exposure. Basner was also a co-author on this review and there are many similarities with the Lancet paper, although this review focuses solely on cardiovascular impacts of noise. The stress model is proposed as a mechanism for the pathway between environmental noise and cardiovascular responses, with the activation of two hormonal systems that help the body to cope with the stressor. These include the activation of sympathetic responses (flight or fight reactions) as well as the release of corticosteroids (defeat reaction). When people are exposed to very sudden or very loud noises, e.g., low flying military aircraft noise, that can be perceived as aggressive or threatening, the fight or flight reaction is triggered. As a result, adrenaline and nor-adrenaline are released. Conversely, high-level noise events beyond the pain threshold and frightening sounds at lower levels increase plasma cortisol, the defeat reaction, aimed at mitigating the damages expected from the stressor. Such stress responses can result in changes in a number of physiological functions and in the homeostasis of several organs, including blood pressure, cardiac output, blood lipids, glucose, electrolytes and others.

The review explained the presence of nocturnal cortical arousals that result from noise as part of the Ascending Reticular Activating System (ARAS), which is part of the body's arousal system. It receives input from several sensory systems, including the auditory system and relays this information to other parts, such as the cardio-respiratory network and through the Thalamus to the Cortex. It is explained that we recognise, evaluate, and react to environmental stimuli even when we are asleep and if such information is passed to the Cortex it can result in a cortical arousal which may disturb or fragment sleep. Interestingly, this is the reason that noise events do not result in an 'all or nothing' response, and not every event will lead to an awakening, but there can be a range of responses depending on the processing of the stimuli.

The differences in arousals between various types of environmental noise (road, rail and air) are discussed, with aircraft generally less likely to induce cortical or vegetative (e.g., heart rate and blood pressure) arousals compared to road or rail noise at the same Sound Pressure Level (SPL). Despite this, aircraft noise is known to illicit higher annoyance responses than the other modes of transportation. The question of habituation is discussed, and generally speaking there is strong evidence for habituation to noise, for example, less arousals being observed in the field setting compared to the laboratory, and differences in responses between first study nights and subsequent nights. It is stressed; however, that habituation is not complete as people react to noise even after several years of exposure in the same environment. There is little known about the individual differences in the ability to habituate to noise, and arousals are still observed even after apparent habituation. Reactions such as increases in heart rate and blood pressure are known to habituate to a lesser degree than cortical arousals.

The review discusses the nocturnal effect of noise on the cardiovascular system and highlights the importance of the findings of Schmidt et al (2013) for supporting a link between nocturnal noise exposure and cardiovascular disease. In addition, it is explained that a sustained decrease in blood pressure during the night (dipping) is important for resetting the cardiovascular system and therefore for cardiovascular health. If environmental noise causes cortical arousals, sleep fragmentation and/or awakenings this may prevent the blood pressure dipping process and contribute to the risk for developing hypertension in those people exposed to night noise for prolonged periods. The authors suggest that there is sufficient evidence for nocturnal environmental noise effects on the cardiovascular system, autonomically in the instances of increases in heart rate and blood pressure, and directly, in terms of vascular function through endothelial dysfunction, that a biological rationale is provided for the increased risk of hypertension, myocardial infarction and stroke in those people with long-term exposure to sufficient noise levels.

## The DEBATS Study

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In 2004, the High Commission of Public Hygiene in France recommended improving the knowledge of the health effects from exposure to aircraft noise. Following this recommendation, the French Ministry of Health and the Airport Pollution Control Authority (Acnusa) initiated a study called DEBATS (Discussion on the health effects of aircraft noise).

DEBATS was conducted by the Gustave Eiffel University and was the first large-scale research program in France to evaluate the possible effects of aircraft noise exposure on the health of airport residents and included an ancillary sleep study. Participants were first interviewed in 2013 at the start of the study, and then at follow-ups in 2015 and 2017.

Several researchers were involved in the DEBATS study. Nassur et al (2019) investigated the effects of aircraft noise exposure on heart rate during sleep in the population living near the Paris-Charles de Gaulle and Toulouse-Blagnac airports. This study was an extension of the DEBATS study and included 112 participants.



Exposure to aircraft noise at home was measured continuously over eight days, with two sound level meters positioned at the home; one outside the bedroom façade and one within the bedroom to measure interior SPL. For one of the eight nights, the participants wore an Actiheart, a monitor that measures and records heart rate. The Actiheart measurements were used to determine the number of heart beats per minute (heart rate, HR) of each participant every 15 seconds during their sleep. The two sound level meters and the Actiheart monitor were synchronized at the beginning of the measurements to the nearest second. The recording dates of the SPL and heart rates did not match for 14 subjects who were therefore excluded from analysis, resulting in measurements from 92 of the 112 subjects being used for a total of 92 nights.

The heart rate at 15 seconds prior to an acoustic event was used as a baseline measure, and compared to the mean HR during the event, and again at 15 and 30 seconds afterwards.

Three variables were therefore constructed:

- HR1 = the difference between the heart rate during the event and the heart rate before the event in beats per minute,
- HR2 = the difference between the heart rate 15 s after the event and heart rate before the event in beats per minute,
- HR3 = the difference between the heart rate 30 s after the event and the heart rate before the event in beats per minute.

A further variable, HRA, was also determined: heart rate amplitude during an acoustic event due to aircraft noise. HRA was calculated as the difference between the maximum and minimum heart rate during an acoustic event, in beats per minute.

The results from regression modelling used to assess the effects of acoustic events linked to aircraft noise on heart rate during sleep is shown in Table 1.

$L_{Amax,1s}$	HR1	HR2	HR3	HRA
	Estimate (95% CI)	Estimate (95% CI)	Estimate (95% CI)	Estimate (95% CI)
Model 1	-0.01 (-0.11;0.09)	0.03 (-0.11;0.17)	0.02 (-0.11;0.16)	<b>0.27 (0.06;0.47)</b>
Model 2	-0.04 (-0.15;0.07)	-0.02 (-0.18;0.14)	-0.04 (-0.19;0.11)	<b>0.34 (0.13;0.55)</b>

Model 1: univariate model including  $L_{Amax,1s}$ ; Model 2: multivariate model including  $L_{Amax,1s}$  gender, age, body mass index (BMI), physical activity, tobacco consumption, alcohol consumption, cardiovascular disease, hypertension, elapsed time after sleep onset, and background 10 min before event; Per 10 dBA increase; HR1 = heart rate during event—heart rate before event; HR2 = heart rate 15 s after event—heart rate before event; HR3 = heart rate 30 s after event—heart rate before event HRA = Amplitude during event; Bold values are statistically significant  $p < 0.05$ .

**Table 1:** Analysis of event-related heart rate response.

The regression models were applied, considering potential confounding factors, to investigate the relationship between energy indicators and heart rate during sleep measured every 15 seconds. Event-related analyses were also carried out in order to study the effects of an acoustic event associated with aircraft noise on heart rate during

sleep. In both models (univariate and multivariate respectively) there was no association found between aircraft noise exposure characterised by  $L_{Amax,1s}$  and the differences between the heart rates at 15 or 30 seconds afterwards and before the event. However, the univariate and multivariate models highlighted a significant positive association between  $L_{Amax,1s}$  and the heart rate amplitude during an aircraft noise event (HRA). When the analysis was limited to only those participants who had lived at the same address for at least 5 years, the results remained unchanged, suggesting no evidence of habituation.

At the ICBEN Congress, 2021, Evrard et al presented an overview of the DEBATS study on the health effects of aircraft noise. Over 1,200 participants living around Paris-Charles-de-Gaulle, Lyon-Saint-Exupéry and Toulouse-Blagnac airports were interviewed in a face-to-face questionnaire study in 2013. The study comprised three methodological elements: an ecological study, a longitudinal study, and an ancillary sleep study.

The ecological study investigated aircraft noise and mortality from causes such as cardiovascular disease in general, ischemic heart disease, including myocardial infarction, and stroke, using mortality data from the French Centre on Medical Causes of Death.

The longitudinal study aimed to examine the relationship between aircraft noise and the mental and physical health of residents, including annoyance through the face-to-face interviews at residents' homes. The first dataset was collected in 2013, with follow-up studies in 2015 and 2017. The annoyance response was measured using the ICBEN five-point verbal scale. Self-rated health status was assessed, and the effects of sleep were measured using total sleep time and feelings of tiredness on waking. Salivary cortisol was collected first thing in the morning and just before bedtime and blood pressure was assessed by the interviewer. Psychological distress was assessed using the General Health Questionnaire.

The ancillary sleep study used a subset of 112 participants from the longitudinal study, and measured actimetry and heart rate. Aircraft noise levels were measured inside and outside of the bedrooms for seven days and seven nights.

The results of the ecological study indicated that an increase in aircraft noise exposure of 10 dBA was associated with an 18% higher risk of mortality for all cardiovascular diseases, 24% for ischemic heart disease, and 28% for myocardial infarction. There was no association found with stroke mortality.

After controlling for confounding factors and restricting the analysis to participants that were living at the same address for five years prior to the study, the results remained unchanged.

The longitudinal study suggested the following associations:

- A 55% increased risk of fair/poor self-rated health status in men with an increase in noise level of 10 dBA  $L_{den}$ , with no evidence of an increase in women.

- The number of Highly Annoyed (HA) people is higher than that predicted by the old EU Miedema curve but lower than predicted by the new EU curve provided by the World Health Organization, in March 2020. (This is consistent with the UK SoNA 2014 findings).
- A risk of sleeping less than six hours per night increased by 60%, and a risk of feeling tired in the morning when waking up increased by 20%, with an increase in noise level of 10 dBA  $L_{\text{night}}$ .
- A disruption of the circadian rhythm of cortisol occurred with an increase in noise level of 10 dBA  $L_{\text{den}}$  (15% decrease in the absolute hourly variation of cortisol, 16% increase in the level of cortisol at bedtime, but no significant variation at wake-up).
- A 34% increased risk of hypertension in men was observed with an increase in noise level of 10 dBA  $L_{\text{night}}$ , with no evidence of an increase in women.

Exposure to aircraft noise did not appear to be directly associated with psychological distress. However, aircraft noise annoyance was associated with it: compared to participants who were not highly annoyed, the risk of psychological distress was increased by 80% in participants slightly annoyed by aircraft noise and multiplied by 4 in those who declared being highly annoyed.

The ancillary sleep study suggested the following alterations to sleep parameters:

- An increase in aircraft noise levels during the sleep period in terms of integrated indicators or noise events indicators was associated with 1.1-1.8 times higher probability of sleeping less than six hours per night (short sleep); and a 1.1-1.6 times higher probability of spending more than nine hours in bed (which can be interpreted as an adaptation mechanism to sleep deprivation).
- An increase in aircraft noise levels during sleep period, quantified in terms of integrated indicators, was associated with a 1.1-1.3 times higher probability of sleep onset insomnia (i.e., a sleep latency greater than 30 minutes).
- An increase in aircraft noise levels during the sleep period, quantified in terms of noise events indicators, was associated with a probability of sleep-maintenance insomnia.
- A 10 dBA increase in the maximum noise level ( $L_{A\text{Smax}}$ ) of an event associated with the passage of an aircraft was associated with an increase in the amplitude of the heart rate during this event (0.34 beats per minute).
- The authors concluded that these findings support the hypothesis that noise is a stressor that activates the sympathetic and endocrine system. They explain that methodological differences in the assessment of highly annoyed people could be the reason why studies conducted since the 2000s found, for the same noise exposure level, higher proportions of highly annoyed people than those observed in the studies conducted before 2000.

Giorgis-Allemand et al also reported findings from the sleep study part of the DEBATS longitudinal study in more detail; in particular self-reported sleep quality and aircraft noise over the four years of the study duration. Time in bed was estimated from the questionnaires as the difference between the time of going to sleep and the time of getting up and characterised as short time in bed ( $\leq 6$  hours) versus normal and long time in bed ( $>6$  hours). For feeling tired after a normal night, participants answered a four-point scale question that was rated as feeling tired (very or rather tired) versus feeling not tired (rather or well rested).

At baseline in 2013, 9% of the total participants had a time in bed less or equal to 6 hours (respectively 8% at first follow-up and 6% at second follow-up) while 30% felt rather or very tired after a normal night (respectively 24% at first follow-up and 23% at second follow-up). A 10 dBA  $L_{den}$  increase in aircraft noise levels was associated with a short time in bed (Odds Ratio OR=3.13; 95% confidence interval CI: 2.14-4.56) and with feeling tired after a normal night (OR=1.28; 95% CI: 1.01-1.61).

Increased aircraft noise exposure was associated with a deterioration of the subjective sleep quality, characterised by a short time in bed and feeling tired after a normal night. The authors explain that these results confirm those of the cross-sectional analyses conducted at baseline in 2013, and support those found in a cross-sectional study around Schiphol airport in Amsterdam (Netherlands) that found an increased risk of tiredness when exposed to higher levels of aircraft noise.

## **TraNQuIL Study (Transportation Noise: Quantitative Methods for Investigating Acute and Long-Term Health Effects)**

In 2019, Saucy et al published findings on the acute triggering effects of aircraft noise at night on cardiovascular mortality in Switzerland. The research presents the methodological approach used to obtain noise exposure assessment and average noise levels in the specific time intervals prior to death.

The aim of this study, TraNQuIL (Transportation Noise: Quantitative Methods for Investigating Acute and Long-Term Health Effects) was to investigate acute effects of aircraft noise on myocardial infarction, stroke and other ischemic cardiovascular causes of mortality by means of a case-crossover study. In addition to assessment of the exposure-response relationships for different time-windows of exposure during the night preceding death, the cumulative effects of several nights preceding the event were looked at.

The case-crossover design allows the investigation of acute health effects for time-varying exposures such as air pollution or noise. The exposure levels at a given time when an event occurs (case events) are compared to the exposure when no event occurs (control events). Due to the daily variation of aircraft movements at Zurich airport, noise exposure varied between study days (case days) and control days. A night flight ban between 23:30 and 06:00 has been in place since 2010, and before that was from 00:30 to 05:00 or 06:00 for approaches and departures, respectively.

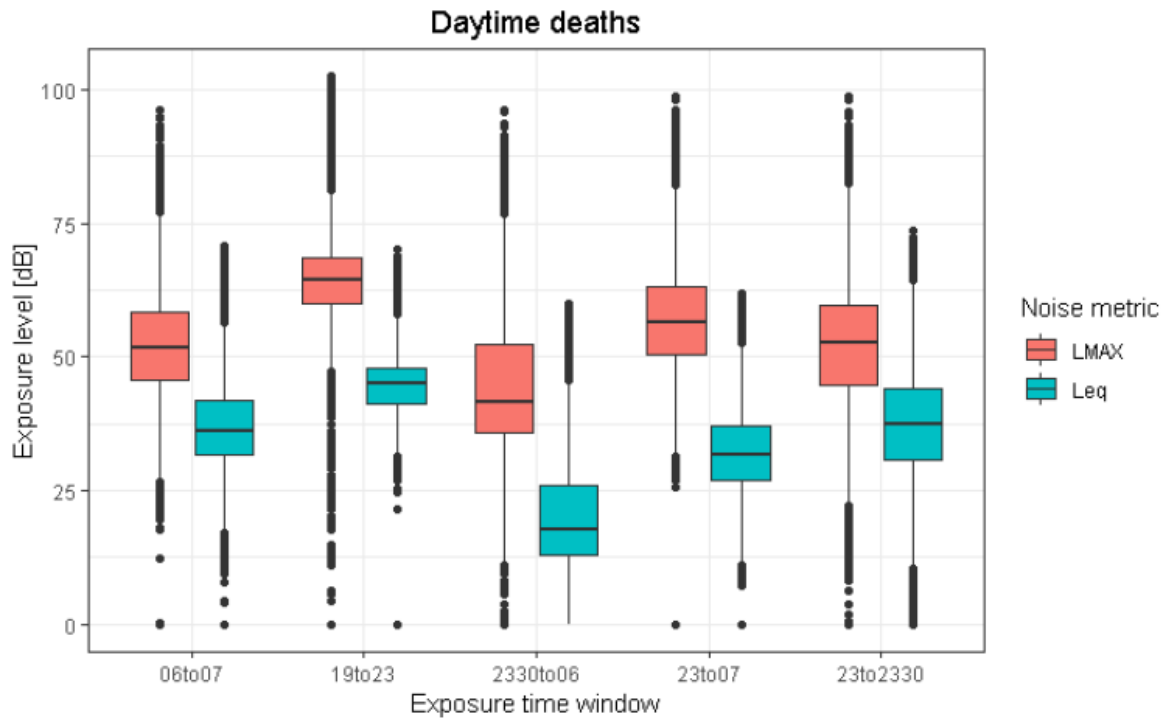
The authors identified all deaths from the Swiss National Cohort occurring near Zurich airport between 2000 and 2014. These included 22,000 cases of cardiovascular disease, and 3,000 Myocardial Infarctions. Outdoor noise exposure at participants' home addresses was calculated for the night preceding death as well as 3 to 4 control nights selected within the same month, using calculated aircraft noise impact for each registered flight. Only those individuals who had potentially been exposed to increased aircraft noise exposure were included in the study. This was determined by the criteria used in the Zurich Aircraft Noise Index, which is an index for the number of highly annoyed and highly sleep disturbed. Noise exposures for each individual at their home address was obtained for the night prior to death and for the control nights, by using the list of aircraft movements which includes detailed information on all flights landing or taking off from Zurich airport.

The authors focussed on assessing only the night time aircraft noise exposure, looking at the effects of noise exposure on mortality during sleeping hours.

The death cases were each matched with 3 or 4 control dates (the same day of the week in the same month), and separate methodology used for deaths occurring at night (23:00 – 07:00) versus the daytime period (07:00 – 23:00). In the death cases occurring at night, noise exposure was calculated for the two hours prior to death. For people who died during the day, the exposure windows were:

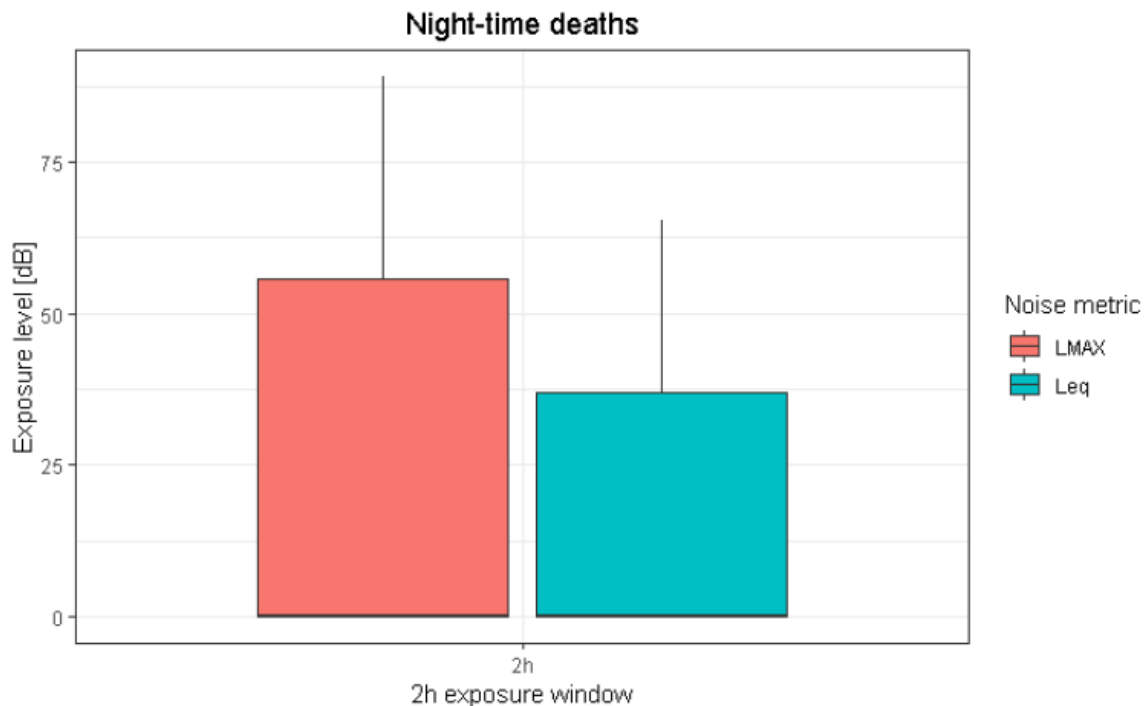
- 19:00-23:00: Evening
- 23:00-23:30: Reduced air traffic
- 23:30-06:00: Flight ban
- 06:00-07:00: morning
- 23:00-07:00: overall night

The results indicated that for both metrics  $L_{Aeq}$  and  $L_{Amax}$ , noise exposure was highest for the evening exposure window, and lowest during the core night. For deaths occurring during the daytime, the average  $L_{Aeq}$  of the time windows ranged from 20-45 dB, and the  $L_{Amax}$  average values ranged between 40 to 60 dB, with the highest values of around 100 dB. This is shown in Figure 2:



**Figure 2:** Boxplot of the noise exposure levels  $L_{Amax}$  and  $L_{Aeq}$  for the different time windows for all events (case and control) for daytime deaths between 2000-2014. Central line represents the median value, squares the interquartile range (IQR) and the whiskers the lower and upper limits ( $-1.5 \times IQR$  and  $1.5 \times IQR$ ). Reproduced from Internoise 2019 proceedings.

For the deaths occurring at night, average  $L_{Aeq}$  for the preceding two hours was 36 dB with maximum values of around 65 dB, and the average  $L_{Amax}$  for this period was 57 dB with maximum values of around 85 dB. These are shown in Figure 3.



**Figure 3:** Distribution of the noise exposure levels  $L_{Amax}$  and  $L_{Aeq}$  for the 2-hour window for all events (case and control) for night-time deaths between 2000-2014. Central line represents the median value, squares the interquartile range (IQR) and the whiskers the lower and upper limits ( $-1.5 \times IQR$  and  $1.5 \times IQR$ ).

The authors explain that the methodology used in this study allows for flexibility with the choice of exposure events, and precision due to the use of the list of movements and previously calculated noise footprints for different aircraft types and air routes. They suggest that this is a suitable method for case-crossover studies looking at short-term or transient effects of noise on health.

Saucy et al also published further results from this study in 2021 on the link between nocturnal aircraft noise and the possible link with acute mortality. This was a case-crossover study on nearly 25,000 people who had died, in the vicinity of Zurich airport between 2000 and 2015.

The rationale for this study was that although the effects of long-term exposure to nocturnal aircraft noise is well studied, there is a need to further understand whether noise exposure also acts as a trigger for acute cardiovascular events and how the timing of noise exposure controls this response. The aim was to investigate if and how night-time aircraft noise can trigger mortality for cardiovascular diseases.

The study involved conducting separate analyses for night-time and daytime deaths, and also tested three different noise exposure metrics to capture the characteristics and evolution of noise over time for various exposure windows.

A case-crossover design methodology was used, which adjusts for any individual confounders that do not vary over a short period of time, such as age, smoking, or socio-

economic status. The authors explain that this approach is particularly well suited to investigate acute risk effects and has been applied to air pollution studies. The study investigated deaths occurring during the day (07:00–23:00), and deaths occurring during the night (23:00–07:00). For the night-time deaths, a 2-hour exposure window preceding death was considered. For deaths occurring during the daytime, the effect of five different exposure windows within the night preceding the day of event were categorised:

- i. overall night preceding the day of death (23:00–07:00)
- ii. late evening (19:00–23:00)
- iii. reduced air traffic reserved for delayed flights (23:00–23:30)
- iv. core night (23:30–06:00)
- v. early morning (06:00–07:00).

The study population was adults over 30-years old, with the cause of death being cited as cardiovascular related, living near Zurich Airport. This was ascertained using the envelope of the Zurich Aircraft Noise Index (ZFI) calculation parameters from 2000 to 2016 for highly annoyed and highly sleep disturbed people. Ischaemic Heart Disease (IHD), Myocardial Infarction (MI), stroke, haemorrhagic stroke, ischaemic stroke, heart failure, blood pressure related death, and arrhythmias were all included as relevant causes of death.

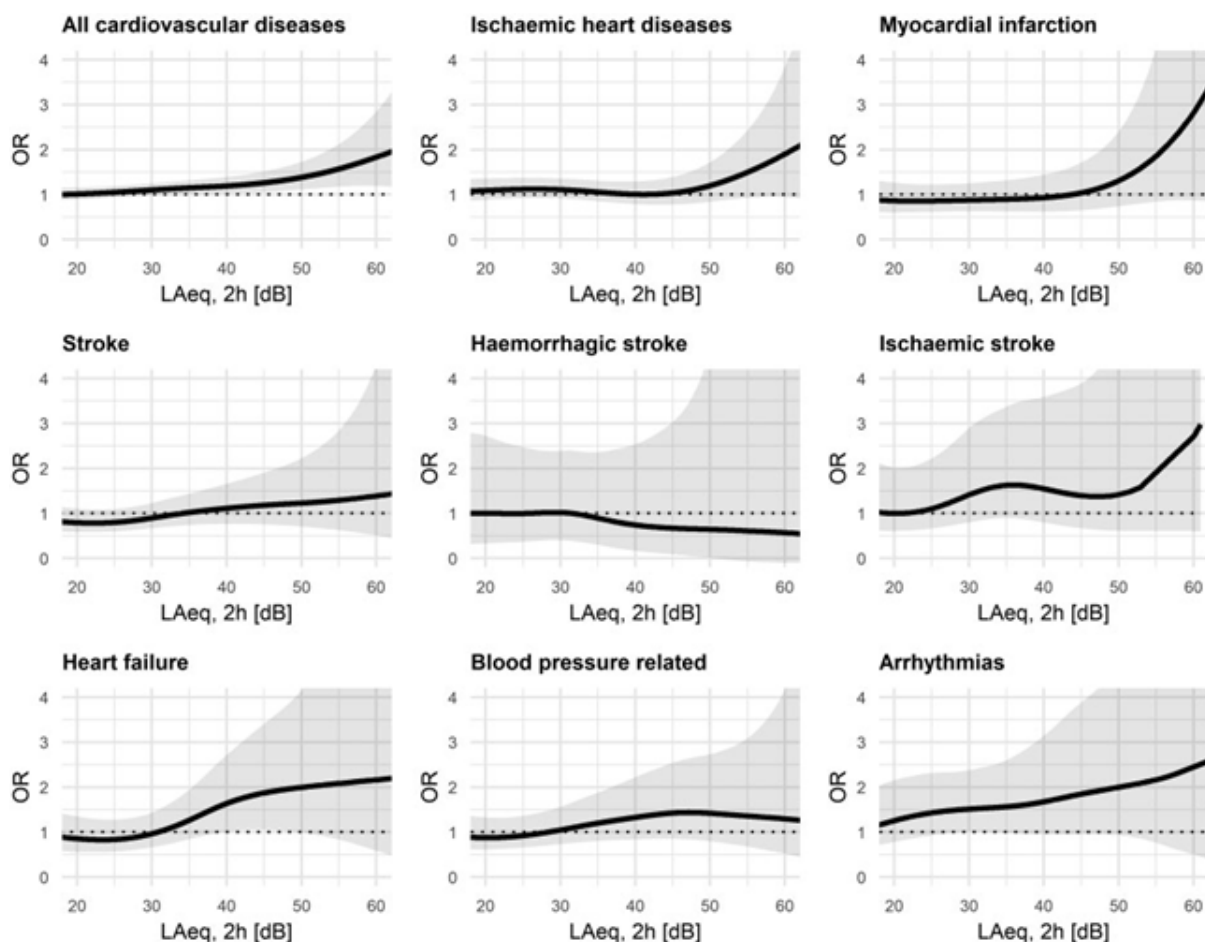
Three noise metrics were investigated:

- average A-weighted equivalent continuous sound pressure level ( $L_{Aeq}$ )
- maximum sound pressure level ( $L_{Amax}$ )
- number of events above threshold 55 dB (Number Above Threshold 55) for the pre-defined time windows.

The association between average aircraft noise and cardiovascular mortality was estimated using conditional logistic regression. 7,641 deaths occurred during the night and 17,245 during the day. The mean  $L_{Aeq}$  ranged from 17.6 to 45.2 dB for the different exposure time windows. On average, all three-noise metrics were highest in the evening time window (19:00–23:00) and lowest in the core night (23:30–06:00).

The results indicated that there was an association between 2-hour aircraft noise exposure preceding the time of a cardiovascular death during the night (Figure 4). This was particularly the case for IHD, MI, heart failure, and arrhythmias. The odds of night-time cardiovascular mortality (all causes) was significantly increased for 2-hour  $L_{Aeq}$  values above 40 dB. The lower number of cases for some diagnoses (e.g., haemorrhagic and ischaemic strokes) resulted in insufficient power to draw any conclusion about the exposure-response relationship.





**Figure 4:** Odds of night-time mortality in relation to 2-hour  $L_{Aeq}$  levels.

The odds of mortality were significantly stronger among females than males, especially for arrhythmias. The researchers estimated that 782 out of 24,886 deaths in the study population could be attributed to aircraft noise (approximately 3%). The association between aircraft noise and night-time cardiovascular deaths was significantly stronger for people living in quiet areas compared to areas with higher night-time levels of road and railway noise, and also for people living in older buildings, most likely with less effective sound insulation. The association between 2-hour  $L_{Aeq}$  and mortality tended to be stronger with decreasing education level and socio-economic status, as well as older age. For daytime deaths, no consistent risk increase was observed.

The study findings suggested that night-time aircraft noise events may trigger cardiovascular deaths, which would explain 3% of all cases of death from cardiovascular cause in the study population living in the vicinity of an international airport if this association was causal. The authors concluded that the study suggests that night-time aircraft noise exposure may be of particular importance in relation to IHD and heart failure, as is also found for long-term exposures.

Wojciechowska et al published a paper in 2022 on the association between blood pressure, arterial stiffness, and aircraft noise in relation to a potential effect of the COVID-19 lockdown. The rationale for the study is that arterial hypertension is well

recognised as one of the negative health consequences of environmental noise. The stress reaction to environmental noise is considered to be a primary causal link to hypertension development, and night-time noise exposure is yet more relevant for cardiovascular disorders, including hypertension, than exposure during daytime. Noise annoyance, along with the noise exposure level, has been shown to increase the risk of hypertension and cardiovascular disorders. Although previous research by Babisch and van Kamp has presented an exposure-response relationship per increase of 10 dB  $L_{den}$  and the associated relative risk of hypertension increasing by 13%, there has not been any evidence to suggest that a decrease in noise exposure would result in a corresponding lowering of risk of hypertension.

In a cross-sectional analysis of a case-control study in 2015, the same authors published the association between increased arterial stiffness (pulse wave velocity PWV) and aircraft noise exposure. In this study, the potential impact of a reduction in aircraft noise exposure on arterial stiffness in people previously exposed to increased aircraft noise was also investigated.

Residents living in two suburban areas of Krakow, Poland, were included in the study to obtain an equal number of participants exposed ( $>60$  dB  $L_{den}$ ) and unexposed ( $<55$  dB  $L_{den}$ ) to aircraft noise. Participants were aged between 40 and 65 years, which was considered optimal for assessing hypertension-mediated organ damage, and time of residence in the given area was a minimum of 3 years. All participants from the original investigation in 2015 were invited for a follow-up evaluation in June 2020, for assessment by the same study protocol. 74 participants in the exposed and 75 in the unexposed group were available for re-evaluation in 2020.

The study was conducted in an outpatient clinic of the University Hospital in Krakow during one visit. Office and 24-hour ambulatory Blood Pressure measurements (ABPM) were performed during the baseline visit and follow-up visit. ABPM measurements were taken every 15 minutes during the day (06:00–22:00 hours) and every 20 minutes during the night (22:00–06:00 hours). Hypertension was defined based on a prior diagnosis, or use of antihypertensive treatment, or elevated office systolic BP (SBP) or diastolic BP (DBP) values or elevated 24-hour SBP or DBP.

Self-reported questionnaires on sleep quality and annoyance were also included, and to explore the potential influence of COVID-19 lockdown on studied parameters, the authors introduced additional items into the questionnaire by asking about lifestyle changes caused by the lockdown.

During the follow-up period between 2015 and March 2020, the exposure to aircraft noise remained constant in the exposed group. In contrast, a marked decrease in the average aircraft noise level occurred in April 2020, resulting in a reduction from 61.7 to 47 dB  $L_{den}$  during the day and from 55.4 to 43.4 dB  $L_{den}$  during the night, as compared with April 2019. From April 2020, the formerly exposed group was exposed to aircraft noise levels similar to the control group. In the latter, the environmental noise exposure conditions did not

change in the corresponding residential area and remained below <55 dB  $L_{den}$  throughout the entire follow-up period between 2015 and 2020.

The results indicated that during follow-up, a significant increase in BMI, the prevalence of hypertension and the percentage of patients treated with antihypertensive medications was observed in the group exposed to aircraft noise. The incidence of arterial hypertension in the exposed group tended to be higher. The exposed participants at follow-up reported significantly lower noise annoyance ( $P=0.006$ ) in comparison to the baseline visit, but still had higher levels than the unexposed group ( $P=0.001$ ). During follow-up, no significant changes were revealed in the unexposed group in comparison to the baseline visit.

Difficulties in falling asleep were more prevalent in the group exposed to aircraft noise compared with the control group at baseline ( $P=0.02$ ). A significant increase in difficulty falling asleep at the follow-up visit was observed in both studied groups. At baseline, >40% of the subjects in the exposed group reported awakenings at night, compared with only 24% in the unexposed group. However, this difference between groups in awakening during the night was no longer significant at the follow-up visit during the lockdown period. Similarly, the significantly higher prevalence of reported fatigue during the day observed in the exposed group at baseline was not maintained at the follow-up visit. Self-reported lifestyle parameters and working habits during the COVID-19 lockdown period did not change significantly between the groups, but did change significantly for both groups comparing with the periods before and after the lockdown began in 2020.

## CHAPTER 3

# The NORAH Study

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In 2015 the results of the NORAH (NOise-Related Annoyance, cognition and Health) study were published. This was a large-scale, longitudinal German study that commenced in April 2011 and continued until 2014 and included 43 researchers from 11 institutes. In order to obtain more insight into the effects of transportation noise, the state-owned Environment & Community Center (ECC) of the Forum Airport and Region (FFR) commissioned the authors to conduct a noise effects monitoring program at Frankfurt Airport before and after the opening of a fourth runway.

The study examined:

- Aircraft noise annoyance and health related quality of life (HQoL) before and after the opening of the fourth runway in comparison to annoyance at other airports;
- Comparison of HQoL and annoyance due to aircraft, railway and road traffic noise; effects of combined transportation noise exposure on annoyance and HQoL;
- Effects of transportation noise on hypertension and cardiovascular diseases and the causal structure of noise exposure, noise reactions, and health effects;
- Effects of changing nocturnal noise exposure at Frankfurt Airport on sleep;
- Noise effects on cognitive performance and quality of life (QoL) in children.

Three work packages (WP) are included in the study:

1. Annoyance and quality of life
2. Sleep and health
3. Children's cognition

As part of the health work package, a blood pressure monitoring study was conducted from July 2012 -July 2013, and July 2013 -2014 with participants residing in the vicinity of Frankfurt airport and who were exposed to at least 40 dB during the day. Over 800 participants were trained on the use of blood pressure meters that were connected to mobile telephones in real time and recorded their own blood pressure measurements each morning and evening for three weeks and then again one year later. In addition, participants completed a questionnaire with information on basic diseases, socioeconomic status, medication, lifestyle, body dimensions and self-reported noise sensitivity. The researchers found no significant link between aircraft noise exposure and blood pressure, heart rate or pulse pressure. Similarly, no significant relationship between road or rail noise exposure and the named outcomes was found.

Dirk Schreckenberg (2016), who was a lead researcher of the NORAH study, published findings on the effects of aircraft noise on annoyance and sleep disturbances before and after the expansion of Frankfurt airport, which were the results of Work Package 1 (Annoyance and Quality of Life). The study was centred on the opening of a new runway at Frankfurt Airport in 2011, with a night curfew from 23:00-05:00. The study examined the impact of aircraft noise on annoyance and reported sleep disturbances before and after these changes by surveying residents living near the airport before the runway opening and in follow-up studies in 2012 and 2013. Over 3,500 residents participated in all three phases of the study. The results suggest that the exposure-response curve for annoyance versus  $L_{eq,24h}$  shifted following the opening of the runway, depending on changes in local sound levels. Self-reported sleep disturbances were reduced after the introduction of the night curfew except for disturbances during shoulder hours. It was concluded that there are several non-acoustic factors which partly explain the changes in aircraft noise reactions.

Uwe Müller presented the results from the follow-on sleep study (Work Package 2, Sleep and Health) within NORAH. Over 200 participants living around the airport had their sleep measured in their own homes by polysomnography on three occasions (three to four nights on each occasion). A sound level recorder simultaneously recorded all noise inside of the bedroom, and the loudness. The first measurements were taken in summer 2011, prior to the change in night flying restrictions and the new North West runway was opened. The other measurements were taken in the summers of 2012 and 2013.

Participants were questioned about their usual sleep habits and were excluded if suffering from conditions such as sleep apnoea, allergies that required medication, or if the family had children under the age of six and therefore potentially had disturbed sleep or were shift workers. In addition, participants were required to have regular sleep patterns. The people who participated in 2011 usually went to bed between 22:00 and 22:30 hours and got up between 06:00 and 06:30. In 2012 and 2013 people also took part that went to bed and got up on average one hour later. This allowed for analysis of shoulder hour periods between 22:00 and 23:00, and 05:00 and 06:00. For the years 2011 and 2012, the measurements were recorded by polysomnography, and in 2013 the researchers used a new method called vegetative-motor method, which combines Electrocardiography (ECG) and body movements to determine awakenings. This method is less expensive and time consuming than traditional polysomnography, which requires multiple electrodes to be accurately attached to the participant.

The findings indicated that there was no large difference in awakenings between 2011 and 2012, although the probability of awakenings was slightly higher in 2011. The main conclusions were that awakening frequency per night decreased from 2011 to 2012 from 2.0 to 0.8 for those participants who went to bed between 22:00-22:30. For participants who went to bed between 23:00-23:30, the frequency of awakening was 1.9 times per night, suggesting that going to bed earlier acts as a protective measure against noise. Comparisons were made for total sleep time, sleep onset latency, sleep efficiency and

time spent awake, and it was found that the overall quantity and quality of the sleep did not change between 2011 and 2012. Interestingly, the findings suggested that participants who exhibit a more negative attitude to aircraft noise show more objectively measured sleep disturbances. It is possible that this is related to noise sensitivity in those particular individuals.

The study also measured self-reported sleep quality as part of Work Package 1. The findings indicated that there was less self-reported sleep disturbance in 2012 compared to 2011 which is unsurprising given the night flight restrictions, but there was an increase in early morning sleep disturbance between the two years. This suggests that the night flight restrictions do not adequately protect against self-reported sleep disturbance in the early morning shoulder hours.

The probability of awakening from a single noise event did not change between 2011 and 2012. Subjective drowsiness and fatigue ratings were at an intermediate level in all three study years. Adaptation to aircraft noise, perception of ambient noise in the residential area, age and chronotype (morningness-eveningness) of the participants influenced the drowsiness and fatigue ratings. The subjective experience of sleep worsened from 2011 to 2013 by 5% and 11%, despite the introduction of the night flight ban, regardless of aircraft noise exposure, suggesting that non-acoustic factors are part of the explanation.

Elmenhorst (2016) authored a study on residents' attitudes towards air traffic and objective sleep quality. This study was part of NORAH and included a sample of 81 residents near Frankfurt Airport with the aim of investigating attitudes towards air traffic and sleep quality measured polysomnographically in the home. Five-point rating scales were used to rate their attitude (1 = negative to 5 = positive) and the necessity of air traffic (1 = not necessary to 5 = highly necessary). The results indicated that residents with a negative attitude towards air traffic (score < 3; N = 28) took longer to fall asleep, spent more time awake after sleep onset, had a reduced sleep efficiency and less deep sleep. Those participants who rated air traffic to be of no or moderate necessity (score < 4; N = 22) slept less deeply also. The results suggest that attitudes to air traffic are significantly associated with objective measurements of sleep quality, but the direction of causality is not yet clear. It remains to be seen whether a negative attitude results in more sleep disturbance, or whether poor sleep quality then results in a less positive attitude towards the air travel.

## CHAPTER 4

# Night Noise and Metrics

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This chapter presents findings since 2014 that address the noise metrics used in night noise and sleep disturbance research.

A Swiss study by Wunderli et al (2016), examined the use of a new acoustic descriptor called Intermittency Ratio (IR), which reflects the ‘eventfulness’ of a noise exposure situation with the possibility of use alongside the common metrics such as  $L_{Aeq}$ .

Regarding noise effects on health and wellbeing, average measures often cannot satisfactorily predict annoyance and health effects of noise, particularly sleep disturbances. It has been hypothesised that effects of noise can be better explained when also considering the variation of the level over time and the frequency distribution of event-related acoustic measures, such as for example, the maximum sound pressure level. However, it is unclear how this is best measured in a metric that is not correlated with the  $L_{Aeq}$  but takes into account the frequency distribution of events and their emergence from background.

Intermittency Ratio (IR) reflects the ‘eventfulness’ of a noise exposure situation with the possibility of use alongside the common metrics such as  $L_{Aeq}$ . Regarding noise effects on health and wellbeing, average measures often cannot satisfactorily predict annoyance and health effects of noise, particularly sleep disturbances. It has been hypothesised that effects of noise can be better explained when also considering the variation of the level over time and the frequency distribution of event-related acoustic measures, such as for example, the maximum sound pressure level. IR is defined as the ratio of the event-based sound energy to the overall sound energy.

The study looked at whether the intermittent characteristics of noise correlated with subjectively perceived intermittency of noise exposure at the homes of Swiss residents, and whether IR could actually contribute to the explanation of noise annoyance and self-reported sleep disturbance.

The preliminary results suggested that the de-correlation of the IR from  $L_{Aeq}$  in the survey sample studies worked relatively well with road traffic noise but less well with railway and aircraft noise, which is surprising given the intermittent nature of aircraft noise. IR was not strongly associated with self-reported perception of intermittency and does not seem to increase or decrease self-reported annoyance or sleep disturbance responses. It was suggested that the situations with high IR, such as an aircraft overflight, have more and longer noise-free intervals, but also more obvious single events, which could trigger physiological responses at night. The authors suggest a possibility for future epidemiological studies on long-term health effects and sleep disturbances may be to consider the use of IR as a supplementary tool to help explain variance.

McGuire et al (2016) from the University of Pennsylvania authored a research paper on the refinement of a methodology for examining the effects of aircraft noise on sleep in the US. This research echoes the need to be able to use cost-effective methods to monitor sleep in large-scale studies, given the high cost and complicated set-up of polysomnography. Actigraphy and electrocardiography (ECG) are explored in this work, which was a pilot study on 80 participants. The results confirmed that participants are able to complete the physiological and noise measurements unattended, however further studies are underway to eliminate the need for staff to enter participants' homes to set up the sound recording equipment and thereby potentially increase response rates.

McGuire and Basner conducted the WHO's evidence review on the effects of noise on sleep. As with annoyance, this involved a comprehensive literature review of the selected transportation noise sources, with the aim of deriving exposure-response relationships per mode of transport. Both polysomnography measured outcomes and self-reported sleep disturbance were included in the review.

Four studies were identified for which the effects of road, rail, or aircraft on polysomnologically measured sleep was evaluated. Two of the studies were by the DLR in Germany and were used to derive exposure-response relationships between the probability of a sleep stage change to wake or Stage 1 and the indoor maximum noise level  $L_{Amax}$ , for road, rail and aircraft noise. A significant association was found between the probability of a sleep stage change to wake or Stage 1 and the indoor noise levels for all transportation modes, though there was no difference observed between the transportation noise sources.

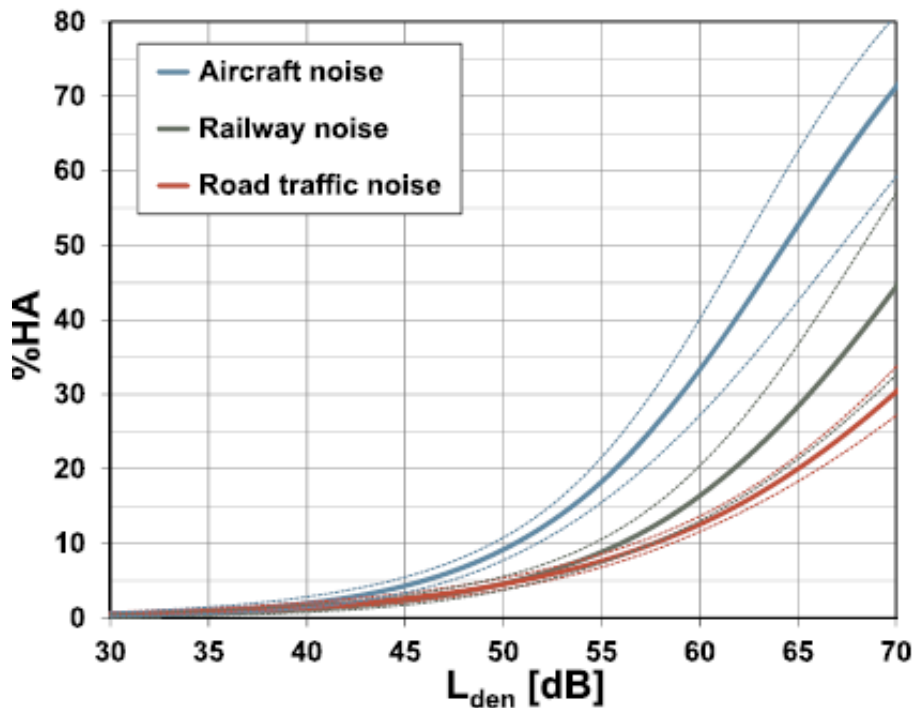
In terms of self-reported sleep outcomes, due to the range of questions used in surveys it was decided to focus on the three most commonly reported sleep outcomes which were awakenings, the process of falling asleep and sleep disturbance which was defined as interference with sleep continuity. A positive association was found between the percentage highly sleep disturbed and  $L_{night}$  levels for road, rail and aircraft noise.

Brink et al (2019) reported results from a survey on exposure-response relationships for road, rail, and aircraft noise annoyance with respect to differences between continuous and intermittent noise. The aim of the study was to look at exposure-response relationships between percentage highly annoyed (HA) and aircraft, road and railway noise measured in  $L_{den}$ . In addition, the authors also wanted to clarify the extent to which the Intermittency Ratio (IR) predicts noise annoyance.

The study used a random sample of over 5,500 residents exposed to transportation noise all over Switzerland, with source-specific noise exposure calculated for each person. Annoyance was measured using the ICBEN 11-point scale, and other outcomes such as sleep disturbance, sleep habits, coping style, general health, noise sensitivity and mental health-related outcomes were also investigated. The survey was carried out in 4 waves at different times of the year.

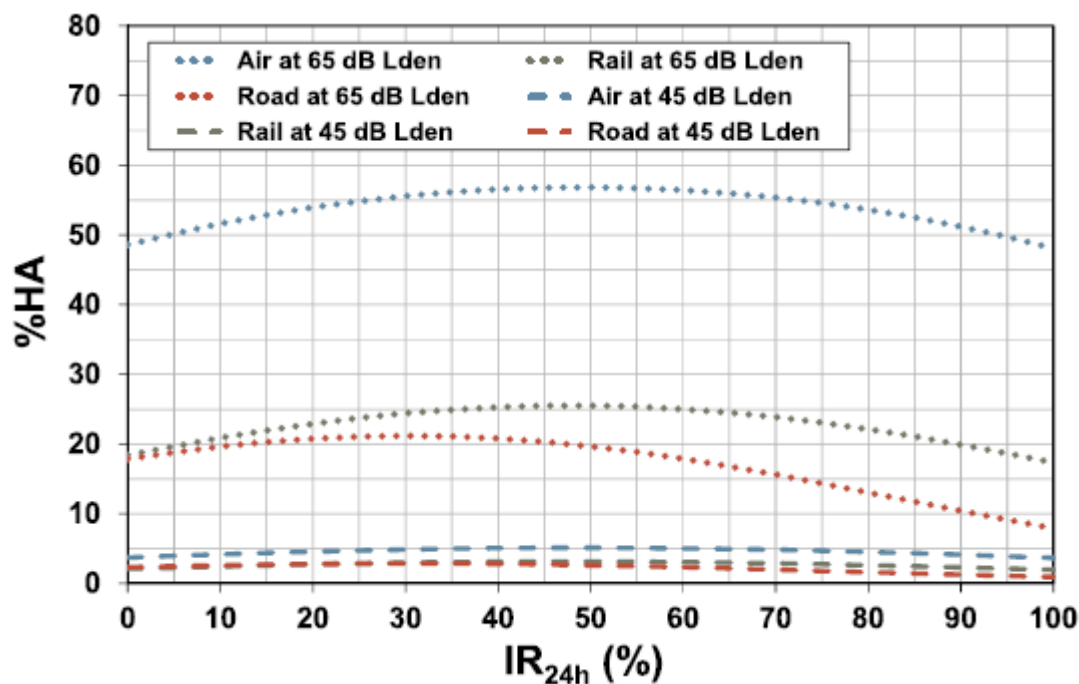


The results indicated that for all noise sources there were significant associations between  $L_{den}$  and %HA after controlling for confounders and independent predictors such as  $IR_{24h}$  (i.e., IR measured over 24 hours), exposure to other transportation noise sources, sex and age, language, home ownership, education level, duration living at the address, temperature, and access to a quiet side of the dwelling. These results are shown in Figure 5.



**Figure 5:** Exposure-response curves for the percentage highly annoyed (%HA) by road, rail, and aircraft noise, including 95% CI (dotted lines).

Figure 6 (below) illustrates the %HA as a function of IR for each of the noise sources at two chosen  $L_{den}$  levels.



**Figure 6:** Percentage highly annoyed (%HA) by road, rail, and aircraft noise as function of IR<sub>24h</sub> for two different L<sub>den</sub> values (45 and 65 dBA L<sub>den</sub>).

The results indicate the aircraft noise annoyance scores are higher than those given in response to railway and road traffic noise at the same L<sub>den</sub> level, and railway noise was more annoying than road noise. In terms of the inclusion of the IR metric, in this study, road traffic noise occurred in very different temporal patterns, from relative continuity to high intermittency. The authors suggest that the inclusion of the IR metric in the exposure-response model for %HA could explain differences of more than 6 dB between road traffic noise exposure situations with low (10%) or high (90%) IR<sub>24h</sub>, possibly due to the effect of different durations of noise-free intervals between events. It is proposed that this study highlights that the temporal distribution of sound energy from road traffic noise probably has an influence on annoyance reactions and therefore could be considered in the rating of road traffic noise in the future. The predictive value of IR was weaker with railway noise and IR was not linked to aircraft noise annoyance.

Tagusari et al (2020) published a paper on the development of a new night-time noise index. This study aimed to develop a new night-time noise index based on neurophysiology and epidemiology. The study involved deriving a formula for predicting the noise effects on sleep, based on a neurophysiological model of brainstem sleep regulation, where awakening was associated with greater electrical potentials in the brainstem.

The researchers then investigated the noise effects on sleep using the results of an epidemiological study that was conducted in the vicinity of the Kadena military airfield in Okinawa, Japan. Thirty volunteers participated in the study. Vibrations of whole-body

movements were recorded using Sheet-Shaped Sleep Monitors (SSSM) for 26 consecutive nights. An SSSM is objective, non-invasive, inexpensive, and has a high time resolution, which is applicable to both short- and long-term measurements. Further, this method enables the investigation of awakening reactions in a volunteer's bedroom. Moreover, this method for measuring whole-body movements may be more favourable than approaches that only measure wrist movement, such as actigraphy. The onset of motility, which was defined by monitor vibrations, was used to index awakening reactions.

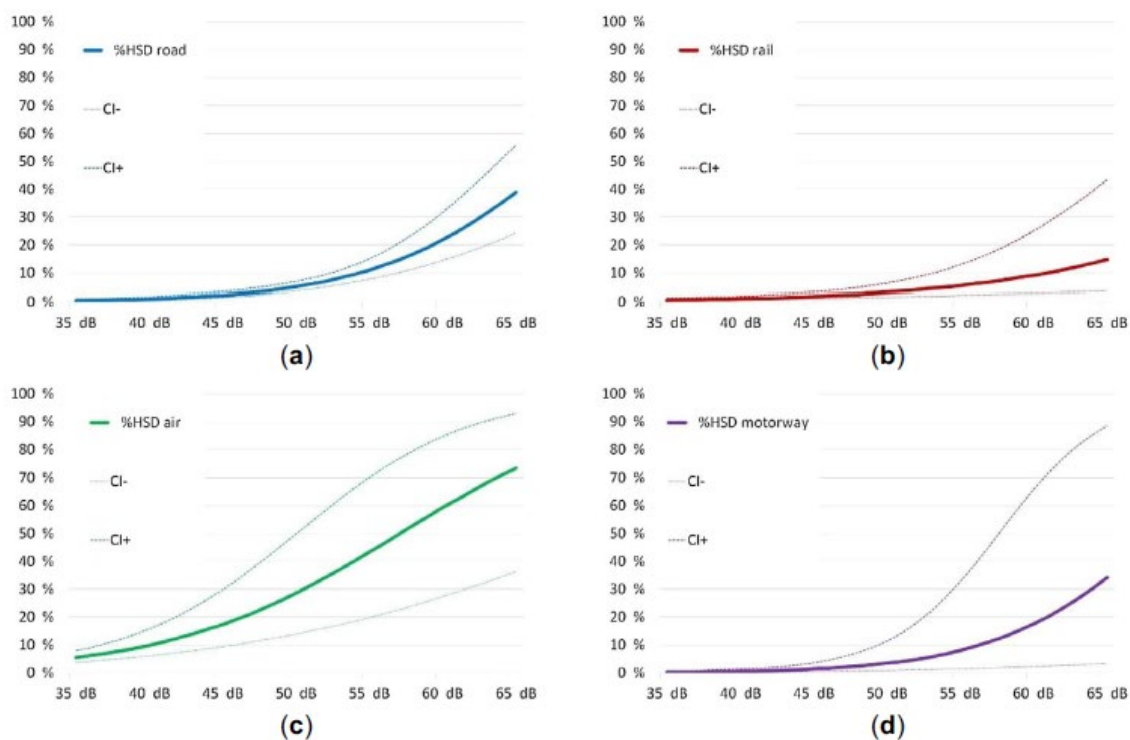
The authors explain that the statistical model developed in the study could correctly predict the fluctuating risk of the onset of motility. They claim that the new index, which is the mean of the sound level above 60 dB, can be successfully used, irrespective of the duration of noise exposure. It was concluded that a new night-time noise index has been derived for evaluating the noise effects on sleep. Furthermore, this is the first study to explain the noise effects on sleep with the consideration of neurophysiology and epidemiology.

Lechner et al (2021) published the results of an Austrian study that involved applying the noise equivalents model for aircraft, rail and road traffic to self-reported sleep disturbance. The authors propose that the cumulative effects of multiple noise sources need to be measured and considered. Models have been developed such as the "dominant source" model and the "annoyance equivalents" model (Miedema), which enable the assessment of the overall noise annoyance caused by multiple transportation sources. The annoyance equivalents model is for annoyance from transportation noise but does not relate to sleep disturbance.

van Kamp et al. on behalf of the Interdepartmental Group on Cost Benefit analysis suggested a meta-analysis for self-reported sleep disturbance for the combination of all transport sources. In this study, secondary data from the project "Total Noise Investigation Innsbruck" was used, with the aim of the study to investigate whether the noise equivalents model is also applicable for self-reported sleep disturbances.

Over 1,031 face-to-face interviews were conducted, and classified into three levels of exposure to road, rail and aircraft noise. The noise exposure groups were ranked using  $L_{den}$  groups of <45, 45-55, >55 dB. Logistic regression analysis was used to predict source-specific exposure-response curves for percentage highly sleep disturbed in relation to  $L_{night}$  levels. The exposure-response curves were adjusted for self-reported noise sensitivity, access to a quiet façade, and existence of noise control windows.

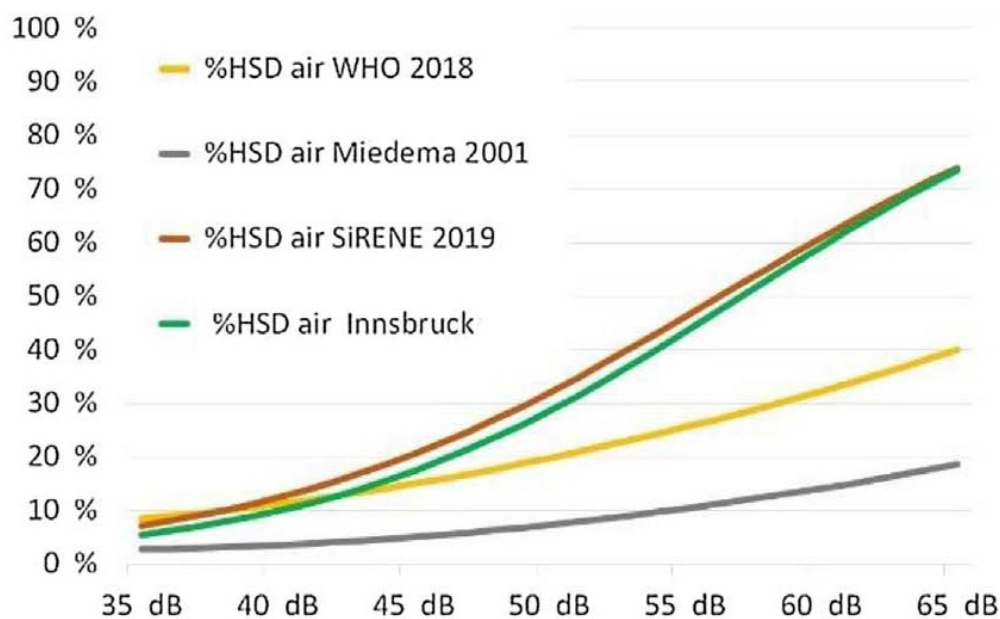
The exposure to road traffic noise ranged from 15 to 63 dB  $L_{night}$ , the exposure to railway noise ranged from 11 to 63 dB  $L_{night}$ , and the range of exposure to aircraft noise was 8 to 48 dB  $L_{night}$ . Exposure-response relationship curves for "highly sleep disturbed" at a cut-off value of 72% for all traffic noise sources are illustrated in Figure 7.



**Figure 7:** (a) Exposure response relationships and their confidence intervals for the percentage of highly sleep disturbed for (a) road, (b) rail and (c) air traffic noise, and (d) for the subgroup motorway noise.

The exposure-response curve is steeper for aircraft noise and self-reported sleep disturbance compared to the other noise sources. The rail noise curve is flatter than the road noise equivalent, especially above 50 dB  $L_{den}$ , where there is a steeper rise in the curve for road traffic. A percentage of 10% “highly sleep disturbed” is expected at 54 dB  $L_{night}$  road traffic noise and 61 dB rail traffic noise. This suggests a 7 dB bonus for self-reported sleep disturbance in relation to railway noise. The 10% highly sleep disturbed level corresponds to approximately 42 dB  $L_{den}$  in this study.

The authors compared these exposure-response curves to other published curves from the WHO (2018), SiRENE (2019) and Miedema (2001) studies. The exposure-response function for air traffic noise in Innsbruck is very similar to the one found in the SiRENE study. Both curves are higher on the scale than the recent WHO curve (Figure 8). A further finding was that the same fit can also be achieved by using a dominant source model.



**Figure 8:** Comparison of exposure-response curves with each other, (b) with WHO 2018, SiRENE 2019 and Miedema 2001 for air traffic noise.

The authors concluded that a sleep disturbance equivalents model for multiple transportation noise sources is suitable for estimating total sleep disturbance within the same range as the annoyance equivalents model. The findings suggest that air traffic at night results in a much higher level of self-reported sleep disturbance than the other transportation noise sources. When comparing the results from this study to those provided by the WHO, it is suggested that it is worthwhile to derive local exposure-response relationships in order to set noise limits.

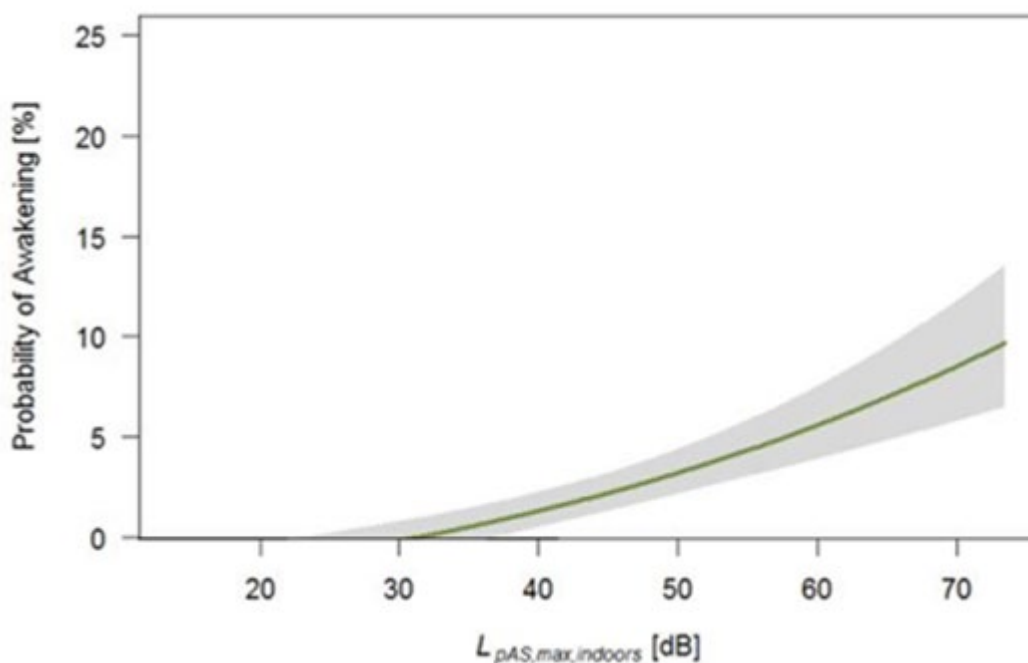
Hauptvogel et al (2021) presented a paper at the ICBEN congress investigating whether aircraft noise-induced awakenings are a more adequate indicator for better understanding of sleep disturbance and therefore night protection around airports. The rationale for this study was that usually, the metrics that are used to describe aircraft noise are based on the energy equivalent sound pressure level  $L_{eq}$ , or its derivatives  $L_{dn}$  or  $L_{den}$ , which respectively integrate a +10 dB penalty for only night noise or a penalty for both the evening noise (19:00-23:00, +5 dBA) and the night noise (23:00-06:00, +10 dBA). The problem with these energy equivalent levels, apart from the inclusion of daytime noise within the metrics, is that several noise events of moderate maximum levels can generate the same equivalent level as a single noise event with a very high maximum level, and these two scenarios could have different effects on sleep disturbance.

The authors explain that this could mean that these metrics are not adequately describing noise effects on sleep and therefore are not eligible for developing a nocturnal protection concept against aircraft noise. They argue that because the body responds to every single noise event (audible overflight) during sleep, the resulting noise events should

therefore be individually characterised by corresponding acoustical quantities (e.g., maximum level and/or SEL). They propose that the probabilities for additional awakenings due to single aircraft noise events must be summed up over the whole night in order to determine the additional noise-induced awakenings (a probability of 100% means one additional aircraft noise induced awakening). For a night noise protection concept, the number of additional aircraft-noise-induced awakenings must then be limited. The study, which was part of the Aviation Noise Impact Management through novel Approaches (ANIMA) project, aimed to calculate and generate a standard exposure-response curve based on previous field studies, which can be generalised over different airports and be used for a night noise protection concept based on human sleep physiology.

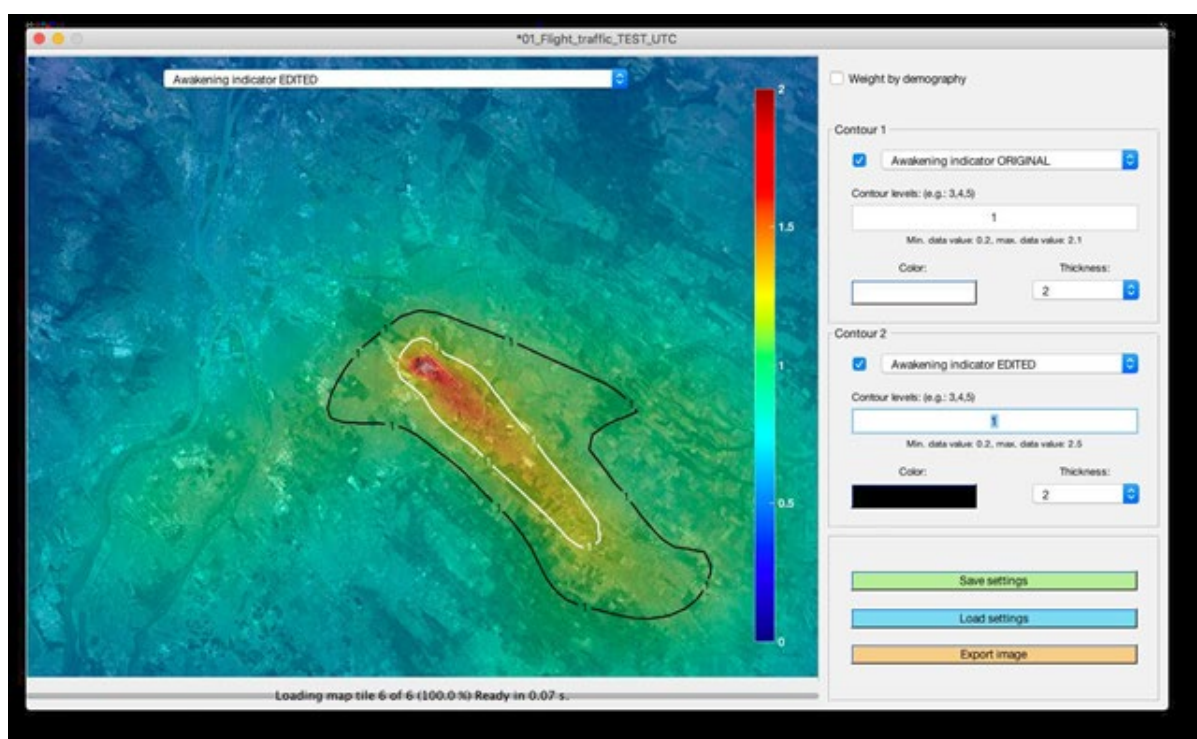
Data from the two German DLR STRAIN and NORAH studies, both of which used polysomnography to examine noise-induced sleep disturbance, were reanalysed and a pooled model was developed. For both the NORAH and the STRAIN study, it was shown that the re-analysis with additional parameters led to statistically better results than the original published models.

As we age, sleep becomes shallower. Therefore, elderly people are generally easier to awake from noise events. Due to a lower number of elderly tested subjects, age was not incorporated into the models so far. The standard exposure-response model which was based on a pooled dataset of the STRAIN and NORAH study, however, does not only consider the model, but also considers age as an influencing personal variable. The exposure-response curve derived from the standard model is depicted in Figure 9.



**Figure 9:** Probability of an awakening as a function of the maximum sound pressure level indoors of one overflight and further acoustical and non-acoustical predictors.

The authors propose to introduce a ‘Virtual Community Tool’, which is software using the standard exposure-response curve, that will enable calculation of additional aircraft noise induced awakenings around airports. Flight schedules, an airport database (containing predicted noise level data a groundborne receptors for all possible aircraft, on all possible flight track combinations) and a corresponding demography database and a buildings insulation quality map can be loaded into the program. To visualise additional awakenings around the airport area, to compare the extension of critical zones defined by different metrics (e.g.,  $L_{den}$  vs Awakening) or to study the effect of changes performed in the Main Window of the interface, a Results Display Window is available to users (Figure 10).



**Figure 10:** Results Display Window showing the increased zone boundaries of 1 additional awakening for an increase of air traffic for a hypothetical airport scenario (reproduced without permission).

The authors explain that the standard model for calculating additional aircraft noise-induced awakenings presented in the paper can be used for (1) communicating the effect of aircraft noise at night in an “easy-to-understand” metric and (2) to develop protection concepts that can prevent physiological acute-effects of aircraft noise.

## Chapter 5

# Night Noise and Effects on Children

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A German study authored by Quehl et al (2019) examined the effects of nocturnal aircraft noise on short-term annoyance in children, and the influence of non-acoustic and acoustic factors. Children are considered a vulnerable group in terms of the potential impact of environmental noise due to their sensitive developmental stage and because of the lack of established coping mechanisms compared to adults. The effect of nocturnal aircraft noise on children has not been widely studied, and this field study examined 51 children aged 8-10 years old living around Cologne/Bonn airport.

The study occurred over four consecutive nights, with aircraft noise measurements taken inside the bedrooms. The number of aircraft movements was also considered. Short-term annoyance was measured the following morning, 30 minutes after waking, via a question recommended by the International Commission on the Biological Effects of Noise (ICBEN). The children were also interviewed on the first day and any moderating psychological factors relating to noise and annoyance were found. Questions to establish noise sensitivity, perceptions of air traffic and attitudes towards aircraft use were also asked within the initial questionnaire.

The results were analysed using logistic regression, and a model for short-term annoyance was established. Only those factors that showed an increased trend effect for annoyance were included in the model, until no further improvement in the model could be obtained. None of the noise metrics, including number of aircraft movements had any effect on short-term annoyance ( $p \geq 0.6$ ) and the odds ratios of all noise metrics were close to 1, meaning that there was little or no effect of noise exposure on annoyance response.

When non-acoustic parameters were included, such as noise sensitivity, attitudes towards air traffic, e.g., 'aircrafts are dangerous', and coping behaviour in the presence of aircraft noise, the model improved to the best fit for predicting short-term annoyance due to nocturnal aircraft noise. The results from this study are quite surprising as the level of night-time aircraft noise and number of movements were not related to short-term annoyance in children, as would be expected in adults. However, when combined with non-acoustic factors such as sensitivity and attitudes towards aircraft, the effect was significant.

Bartels et al (2019) published further findings from the Quehl et al study on nocturnal aircraft noise and annoyance in children. This study examined the effects of night-time aircraft noise on objective and subjective sleep quality in primary school children. The 51 children aged between 8-10 years old were residents in the vicinity of Cologne/Bonn airport, which has a 24-hour operating schedule. Children are known to sleep for longer periods than adults, and across the shoulder hours of the evening and morning and are classed as a vulnerable group to the effects of aircraft noise.



Sleep was measured for four consecutive nights by polysomnography using Electrocardiograms (EEG), Electromyograms (EMG), Electro-oculargrams (EOG) and Electrocardiograms (ECG) along with pulse oximetry (measurements of oxygen level in the blood). Participants also rated their sleep quality and fatigue using a 5-point scale each morning of the study. This was a field study, with sound levels recorded by a sound level meter placed near the children's ears that captured ambient noise levels and aircraft noise events. Aircraft noise was quantified by the number of events above 30 dBA  $L_{max}$  per night.

The variables measured included:

- Sleep onset latency (how long it took to fall asleep)
- Sleep efficiency
- Proportion of slow wave sleep
- Proportion of Rapid Eye Movement (REM) sleep per total sleep time
- Wake duration during sleep period
- Self-rated sleep quality
- Self-rated fatigue in the morning

Linear mixed models were applied in the analysis to investigate the relationship between objective and subjective sleep quality.

The results indicated that a higher number of aircraft noise events at night was associated with a reduction of slow wave sleep by 2.6% and an increase in waking during the sleep period by 1.2%. Sleep onset time was 3.3 minutes longer in those nights with higher aircraft noise exposure. The subjective measures of sleep quality and fatigue were not associated with an increase in aircraft noise exposure. Self-rated fatigue was related to longer wake durations during the total sleep period.

The authors point out that there is evidence to suggest that disruption of slow wave sleep can appear to increase the risk of metabolic, cognitive and cardiovascular diseases, and that the effect of nocturnal aircraft noise in children needs to be further investigated. Cologne/Bonn airport, with its 24-hour operating schedule, is different to other airports that implement a night flight ban, and it has a moderate number of movements during shoulder hours; other airports have fewer movements.

The results suggested that self-reported measures did not correlate with objective measurements in children, a finding that is often seen in studies on adults also. The authors state that this indicates the need for objective measurements to be included in studies investigating the effect of nocturnal aircraft noise and the impact of sleep parameters.

Bluhme et al (2022) published the results from a longitudinal study on the association between nocturnal transportation noise and sleep during the first year of life. The rationale

for the study was that whilst the effects of transportation noise on sleep in adults are well studied, with impacts including reduced sleep duration, decreased self-reported sleep quality, changes in sleep architecture with decreased proportions of deep sleep and increased sleep fragmentation, the impacts of such noise on infants remain not understood. This study investigated the relationship between nocturnal transportation noise and actimetry-derived habitual sleep behaviour across the first year of life.

The study included 144 healthy infants (63 girls, 81 boys). Nocturnal (23:00–07:00) transportation noise (road, railway, and aircraft noise from major airports in Switzerland: Basel, Geneva, Payerne, Zurich) was modelled at the infants' individual places of residence. Annual mean equivalent continuous sound pressure levels ( $L_{Aeq}$ ) were modelled for the geographical coordinates of each participant's place of residence. Using actimetry, the authors recorded movement patterns for 11 days in a longitudinal design at 3, 6, and 12 months of age and measured the sleep composites of night-time sleep duration, activity, and variability.

The results indicated that night-time transportation noise was unrelated to sleep composites across the first year of life ( $p > 0.16$ ). Further analyses of an interaction between noise and the existence of siblings indicated an association between night-time transportation noise and sleep duration in infants without siblings only ( $p = 0.004$ ).

The authors concluded that the data provides novel evidence that infants' objectively assessed sleep during the first year of life generally seems well-protected against external disturbance, for instance by nocturnal transportation noise. However, individual noise sensitivity varies, and those infants who grow up in a sleep protective environment (for instance without noise from siblings) may be more sensitive to the adverse effects of transportation noise on sleep.

Raess et al (2022) studied the association between community noise and children's cognitive and behavioural development in São Paulo, Brazil. The authors explained that although noise exposure has been associated with adverse cognitive and behavioural outcomes in children, evidence on longitudinal associations between community noise and child development in low- and middle-income countries is rare. The study investigated associations between community noise and behavioural and cognitive development in pre-school children between 3 and 6 years old.

Child development data from the São Paulo Western Region Birth Cohort was linked with average ( $L_{den}$ ) and night-time ( $L_{night}$ ) community noise exposure at children's homes, estimated by means of a land use regression model using various predictors (roads, schools, greenness, residential and informal settlements). The Strengths and Difficulties Questionnaire (SDQ) and Regional Project on Child Development Indicators (PRIDI) were the measured outcomes at 3 years of age and the Child Behaviour Checklist (CBCL), and International Development and Early Learning Assessment (IDELA) were the outcomes at 6 years of age. Regression models were used to examine the relationship between noise exposure and development.

Data from 3,385 children at 3 years of age and 1,546 children at 6 years of age were analysed. The mean  $L_{den}$  and  $L_{night}$  levels were 70.3 dB and 61.2 dB, respectively. The results indicated that a 10 dB increase of  $L_{den}$  above 70 dB was associated with a 32% increase in the odds of borderline or abnormal SDQ total difficulties score (OR = 1.32, 95% CI: 1.04; 1.68) and 0.72 standard deviation (SD) increase in the CBCL total problems z score (95% CI: 0.55; 0.88).

In longitudinal analyses, each 10 dB  $L_{den}$  increase was associated with a 0.52 SD increase in behavioural problems (95% CI: 0.28; 0.77) and a 0.27 SD decrease in cognition (95%-CI: 0.55; 0.00). The results above 60 dB  $L_{night}$  were similar. The authors conclude that the results indicate that exposure to community noise is not only associated with increased behavioural difficulties at both ages 3 and 6, but also predicts increases in behavioural difficulties as well as cognitive declines in this age window. The findings suggest that community noise exposure above 70 dB  $L_{den}$  and of 60 dB  $L_{night}$  may impair behavioural and cognitive development of preschool children.

## CHAPTER 6

## Economic Impacts of Nocturnal Aircraft Noise

Ribeiro et al (2019) authored a paper on the health impact of noise in the greater Paris metropolis, focussing on healthy life years lost. Bruitparif (a non-profit environmental organisation responsible for monitoring the environmental noise in the Paris agglomeration) designed a methodology for assessing health impacts per square of territory and per municipality within Paris. Using calculation of Disability Adjusted Life Years (DALYs), the paper describes the impact of transportation noise sources (road, rail and aircraft) on the various regions of Île de France (the area of Northern Central France, surrounding Paris). Within the Île-de-France region, 14 urban agglomerations representing a total of 436 municipalities and 10.1 million inhabitants are included: the Greater Paris Metropolis (131 municipalities, nearly 7 million inhabitants) as well as 13 agglomeration communities or urban communities.

Bruitparif used the methodology recommended by the World Health Organisation (WHO) to calculate DALYs, alongside maps with a 250 m<sup>2</sup> grid and at the level of the municipality to demonstrate the impact of transportation noise on health. Statistical results were provided for the area of study as a whole, as well as for each urban agglomeration, and for each municipality.

The results indicated that transportation noise is responsible for the loss of 107,766 DALYs every year within the region of Île-de-France. The results broken down further into annoyance and sleep disturbance can be seen in Table 2. 43% of total DALYs are lost due to annoyance, and those lost to sleep disturbance account for 57% of the total.

DALY	Road	Rail	Air	Total
Sleep disturbance	33,613	15,088	12,227	60,929 (57%)
Annoyance	31,994	8,352	6,491	46,837 (43%)
<b>Total</b>	<b>65,607 (61%)</b>	<b>23,440 (22%)</b>	<b>18,718 (17%)</b>	<b>107,766</b>

**Table 2:** DALYs lost to transportation noise in the Paris agglomeration.

Road noise is the largest contributor to DALYs, with 61% of the total being due to road noise, 22% attributed to rail noise and 17% associated with aircraft noise.

The authors state that the DALYs lost every year within the region of Île de France have an economic cost of 5.4 billion Euros per year. Noise pollution is the second-highest cause

of death within environmental risk factors in urban environments, with air pollution being the leading cause of death. When compared with previous results for this region between 2011 and 2015, the estimate of the number of DALYs lost to transportation noise has risen 43% (75,000 to 108,000). The figure of aircraft noise-related DALYs has risen by a factor of 3.7, with those related to rail noise increasing by a factor of 3.5. This is due to the incorporation and use of the new exposure-response relationships and limits recommended by the WHO in their update to their Guidelines in October 2018. These guidelines define the recommended values for exposure to transportation noise, as well as new exposure-response relationships that make it possible to compare levels of exposure to noise, as estimated by strategic noise maps, and the main health effects of noise.

The average citizen within this region now loses 10.7 months per lifetime, compared to 7.3 in 2015. The study has revealed that in certain sectors exposed to multiple aircraft and land-based transportation noise sources, the individual health risk is now greater than 3 healthy life-years lost compared to 18 months in 2015.

The authors explained that this study may be used to highlight where best to focus resources by assisting stakeholders in preparing the various environmental noise action plans in 2019.

Fenech and Rodgers (2020) from Public Health England authored a paper on valuing the impacts of noise on health and compared current UK exposure-response relationships with the WHO Environmental Noise Guidelines (2018). The paper examines the studies that contributed to the exposure-response relationships in the two documents that inform UK valuation of noise-induced health effects published by Defra and IGCB(N) and compared them to those that informed the more recent WHO Environmental Noise Guidelines. The paper discusses in detail how the UK guidance came about, and the formation of the IGCB(N). The findings from IGCB(N) in 2010 led to the inclusion of the following recommendations:

- Inclusion of the risk of Acute Myocardial Infarction (AMI) into the monetary valuation
- Continuation of using monetary values for annoyance based on a hedonic pricing approach
- To use indicative quantification of hypertension and sleep disturbance impacts.

Following the publication of the WHO's Burden of Disease (BoD) report in 2011, which described a methodology to quantify the burden of disease caused by noise in terms of Disability Adjusted Life Years (DALYs), Defra published their own guidance in 2014 and recommended:

- Using a DALYs approach to quantify and monetise noise annoyance and sleep disturbance impacts
- Using a two-step approach to monetise hypertension effects
- Using the methodology from the 2010 IGCB(N) report to value AMI.

The paper goes on to explain the current UK guidance on sleep disturbance, which recommends that sleep disturbance impacts are monetised where it is proportionate to do so. The paper describes the equation for calculating the value of sleep disturbance; and explains Disability Weighting (DW) and the current exposure-response functions for sleep disturbance due to road traffic noise, railway noise and aircraft noise (quantified using the  $L_{\text{night}}$  metric). The equations for these are equivalent to those in the BoD report.

The authors compare the current UK guidance for sleep disturbance to those presented in the WHO Guidelines and explain that for aircraft noise the exposure response function is higher in terms of percentage Highly Sleep Disturbed (HSD) throughout the noise exposure range 40-65 dB  $L_{\text{night}}$  in the WHO Guidelines than those derived by Miedema and Vos, which feature in the current UK guidance. Basner and McGuire offered the following explanations as to why this may be the case:

- Different methodologies were used to derive the data
- Year of study – during and after 2000 in the WHO Guidelines; prior to 2004 in the Miedema and Vos' analyses
- Locations of studies – Miedema and Vos' analyses are largely from European countries; the WHO used data from many studies conducted in Asian countries in their meta-analysis
- Question wording – older studies ask about annoyance due to sleep disturbance; more recent studies ask specifically about symptoms of sleep disturbance, awakenings and difficulty falling asleep.

In terms of annoyance, the authors also compare the UK guidance with the WHO Guidelines. Again, the WHO dataset shows higher percentage Highly Annoyed (HA) than in the curve from the Miedema and Oudshoorn study used for the UK guidance. Six of the studies used in the WHO meta-analysis are from the HYENA study, designed to examine hypertension in populations around airports. Guski et al offered some explanations as to why the difference may have occurred, which included reference to the HYENA studies only including participants between the ages of 45-70 years, which may have introduced some bias towards higher degrees of annoyance. In a later published study by Guski et al, the data from seven more recent studies (post 2014) were added to the dataset, including the UK Survey of Noise Attitudes (SoNA) study. Despite the additional more recent data, no significant changes were observed in the exposure-response function compared to the WHO Guidelines data for aircraft noise and annoyance.

The paper also discusses the discrepancies between the two sets of guidance in terms of transportation noise and cardiovascular disease and discusses some of the reasons why this may be the case. In conclusion, the authors suggest that due to the age of the studies used to inform the UK guidance, there is a need for new research on noise annoyance and sleep disturbance effects in the UK.

## CHAPTER 7

# Aircraft noise and sleep disturbance: Other findings

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Janssen et al (2014) examined the effect of numbers of aircraft noise events on sleep quality. The rationale for this study was that although WHO recommends the use of  $L_{\text{night}}$  as the primary indicator for sleep disturbance, there is some evidence to suggest that the number, characteristics and distribution of individual noise events throughout the night can impact sleep disturbance. The authors explain that the WHO Night Noise Guidelines (NNG) and the European Noise Directive (END) allow the use of both the maximum sound pressure level ( $L_{\text{Amax}}$ ) and sound exposure level (SEL) in addition to  $L_{\text{night}}$  to predict sleep quality.

The aim of the study was to investigate whether  $L_{\text{night}}$  sufficiently represents the number of aircraft noise events that contribute towards prediction of sleep disturbance by motility, and the association between sleep quality and numbers of events. The second aim was to investigate whether the number of events at a given  $L_{\text{night}}$  has an additional predictive value. In addition, it was explored whether the total number of events should be taken into account for the prediction of sleep quality, or only the number of events exceeding a certain sound pressure level.

Data was collected around Schiphol airport between 1991 and 2001 from 419 residents at varying distances from the airport. The study lasted eleven days and participants were requested to complete morning and evening diaries, reaction time tests, sleepiness scales and to wear an actiwatch for the duration of the study. They were exposed to normal aircraft noise levels at home, all of which were within 20 km of the airport and selected based on their  $L_{\text{night}}$  noise levels. Sleep quality was determined by self-reported sleepiness and actigraphy, which also measured motility.

The results indicated that additional information on the overall number of events does not improve the prediction of sleep quality. The number of events of higher noise levels ( $> 60$  dB  $L_{\text{Amax}}$ ) was associated with an increase in motility, which suggests a decrease in sleep quality. There was no effect of number on self-reported sleep quality. The authors suggested that the number of events is more or less adequately represented by  $L_{\text{night}}$  and only the number of high noise level events may possibly have additional effects on sleep quality as measured by motility. It is proposed that in addition to  $L_{\text{night}}$ , the number of events with a relatively high  $L_{\text{Amax}}$  could be used as a basis for protection against noise-induced sleep disturbance.

Maria Foraster from the Swiss Tropical and Public Health Institute from Basel investigated annoyance reactions and the risk of physical inactivity (2016). The theory behind this work was that annoyance from transportation noise and resulting sleep disturbance may then in turn lead to a reduction or lack of physical activity. Perceived stress and unconscious stress resulting from noise can both lead to sleep deprivation. In addition, annoyance with

the neighbourhood due to noise may reduce the willingness to go outside and exercise locally. The study had two aims:

- To investigate whether there is an association between noise annoyance at home and physical activity, and
- Is there any effect modification by gender and noise sensitivity?

3,622 participants aged 30-38 years were assessed as part of a large study cohort in Switzerland between 1991 and 2011. Annoyance was assessed on the 11-point annoyance scale. Sufficient physical activity was defined as at least 150 minutes of exercise per week. The results indicated that 60% of the study population were active, and there were fewer tendencies towards high annoyance scores in those that were physically active. Road traffic noise was responsible for the highest degree of annoyance, followed by aircraft noise and then railway noise. There was a significant association between long-term annoyance to transportation noise (on average 20 years) and being physically inactive at the end of that period.

Physical inactivity was strongest amongst those people who had reported sleep deprivation, particularly for night-time annoyance to road traffic noise. No effect modification was observed for gender or noise sensitivity, so these factors do not explain the association. Foraster concluded that noise annoyance at night may contribute to cardiovascular diseases through a decrease in physical activity, and this relationship may be stronger in those people with impaired sleep, especially due to road traffic annoyance at night. This is the first study to investigate transportation noise and physical activity with relation to cardiovascular health endpoints. Further studies are needed to confirm these results and to ascertain the pathways that may be responsible for decreased activity.

Griefahn (2017) authored a study on the effects of traffic noise on autonomic arousals during sleep.

Noise causes transient excitations, or arousals, of both the autonomic and the central nervous system during wake and sleep. These effects are non-specific and are evoked by other environmental stressors as well.

Noise causes non-specific arousals:

- of the central nervous system as measured with the EEG and
- of the autonomic nervous system as indicated by alterations of autonomic functions.

Cortical arousals are transient excitations of the central nervous system (CNS) that are measured with the electroencephalogram (EEG).

Autonomic or subcortical arousals are transient excitations of the autonomic nervous system (ANS) that are indicated at the periphery by alterations of various autonomic functions. In general, noise reduces the cardiac output, and increases the peripheral



resistance while decreasing the width of peripheral blood vessels and elevating the blood pressure; noise causes alterations of heart rate, of ventilation, of skin resistance etc.

This study examined the effects of different traffic noise sources, presented with the same sound pressure level, and the results indicated that different responses were observed. Heart rate acceleration is steepest; the maximum is highest and is first reached with railway noise. For road vehicles the maximum occurs somewhat later and is less pronounced. Aircraft noise causes the lowest and latest maximum. The minimum occurs at the same time for both surface transport noises but almost 10 seconds later for aircraft noise.

Griefahn suggested that when it comes to the assessment of sleep disturbances of residents living near airports, along railway lines or busy streets, near military training camps or industrial sites, evaluations must focus on the specific noise exposure and cannot be deduced from the effects of other noises. However, research in this area is still insufficient and therefore these preliminary conclusions are still based on studies with noises played in the laboratory rather than in the field.

Smith et al (2019) published findings of a study into self-reported sleep disturbance from aircraft noise around Atlanta airport. Surveys were sent by post to randomly selected homes around Atlanta airport, which resulted in 290 respondents. Outdoor aircraft noise  $L_{\text{night}}$  levels between 22:00 – 07:00 were calculated for each household, and logistic regression analysis was applied to each response variable. In addition to questions relating to sleep quality, noise-induced sleep disturbance, coping strategies and health conditions, the questionnaires included questions on age, sex, BMI, education and employment.

The results indicated that  $L_{\text{night}}$  levels were significantly associated with a decrease in sleep quality, increased frequency of difficulty falling asleep, and increased difficulty in staying away during daytime hours. An increase in  $L_{\text{night}}$  noise levels were also associated with a significant increase in noise-induced sleep disturbance and annoyance. Outcomes such as diagnosed sleep disorders, hearing impairment, hypertension, arrhythmia, migraine and diabetes were not associated with aircraft noise levels at night.

Elmenhorst et al (2019) examined the effects of road, railway and aircraft noise on sleep in three laboratory studies. There are many studies on annoyance that suggest that railway noise is the least annoying, followed by road traffic noise, with aircraft noise causing the highest rate of annoyance. The authors explain that with sleep disturbance, the order is often reversed i.e., aircraft noise is the least likely to cause awakenings, with railway noise producing the highest number of awakenings. This study pooled data from three laboratory studies that were conducted at the German Aerospace Centre, Cologne and Leibniz Research Centre for Working Environment and Human Factors in Dortmund. Nearly 110,000 noise events were produced, and resulting awakenings were assessed by polysomnography in 237 participants. Polysomnography is the continuous recording of specific physiologic variables during sleep. Polysomnography typically records brain wave changes (electroencephalogram), eye movements (electrooculogram), muscle tone

(electromyogram), respiration, electrocardiogram (EKG), and leg movements. This technique, whilst being the gold standard for studying sleep disturbance, is time-consuming and expensive, and there is a lack of large-scale studies of this nature, hence the decision to pool the three studies:

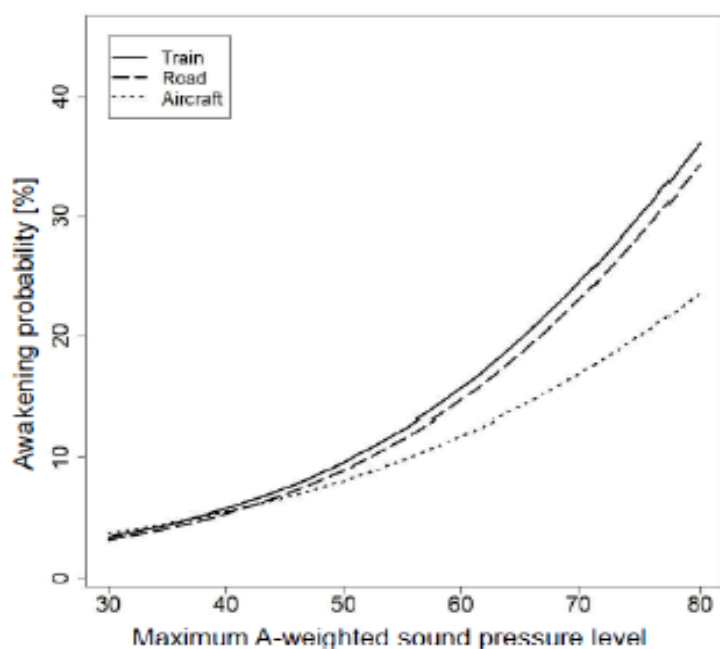
- STRAIN (Study on human specific response to aircraft noise) study at the German Aerospace Centre, Cologne: 112 participants (65 female, 47 male) with an average age of 38.1 years.
- AIRORA (Effects of air, road and rail traffic noise) study at the German Aerospace Centre, Cologne: 72 participants (40 female, 32 male) enrolled in the study with a mean age of 40.3 years.
- IfADo study at the Leibniz Research Centre for Working Environment and Human Factors, Dortmund: 53 participants (26 female, 27 male) were examined with a mean age of 23.4 years.

The exact design and methodology for each study is described in detail in the paper. An overview of the number of events for each noise source, and participants in each study is shown in Table 3.

Category	STRAIN Study	AIRORA Study	IfADo Study	Total Number
Number of participants	112	72	53	237
Number of road noise events	-	9908	25,739	35,647
Number of railway noise events	-	10,014	17,666	27,680
Number of aircraft noise events	25,479	9741	11,289	46,509
Total number of noise events	25,479	29,663	54,694	109,836

**Table 3:** Number of participants and noise events used for analyses from the three major traffic noise sources that were played back in the three different studies.

In terms of the regression model, the predictors A-weighted Sound Pressure Level (SPL) and Tr (Tr = steepest slope of the event curve as rise time of the maximum A-weighted SPL of a noise event [dB/s]) were both highly significant acoustical predictors for awakenings. There was a significant interaction between maximum a-weighted SPL and aircraft noise, which indicated that the slope of the exposure-response curve was not as steep as those found for road and railway noise. This is shown in Figure 11:



**Figure 11:** Ranking of the probability for sleep stages changed to awake and Stage 1 due to air, road and railway noise depending on the maximum A-weighted sound pressure level of the noise event.

The results indicate that the probability to wake from equal maximum A-weighted sound pressure levels (SPL) was highest for railway noise, followed by road noise and aircraft noise was the least likely noise source to result in awakenings at the same SPL. There was no significant difference in the awakening probability between road and railway noise ( $p = 0.99$ ). The authors point out that at 70 dB SPL, it was more than 7% less likely for a person to wake up due to aircraft noise compared to railway noise. This is the opposite to the findings for annoyance responses, and the authors stress the importance of including sleep metrics, in addition to annoyance levels, in noise legislation decision-making.

Basner et al (2019) reported on the results from a pilot field study on the effects of aircraft noise on sleep around Atlanta airport. The aim was to assess whether it was possible to obtain acoustical and physiological data without the presence of an investigator and with the equipment sent to the participants by post for their own application of electrodes and data collection. If successful, this protocol would provide a more objective measurement of sleep disturbance in a field study setting, but without the high cost of requiring investigators to be present for each participant for each set-up of recording equipment.

From 407 respondents to a postal recruitment drive aimed at residents experiencing  $>35$  dB  $L_{Aeq,8h}$  (23:00-07:00, outdoor), 34 participated in a field study at their homes over five consecutive nights. The results indicated that after adjustments for sociodemographic factors, outdoor night-time aircraft noise was significantly associated with self-reports of decreased sleep quality, with those people living in the 50-55 dB  $L_{night}$  region reporting significantly worse sleep quality than those in the reference group of 35-40 dB  $L_{night}$ . Participants in the  $>50$  dB  $L_{night}$  regions were more annoyed than those in the reference

group. Night-time aircraft noise exposure was also associated with difficulty falling asleep, staying awake during the day and increased difficulty concentrating.

The authors concluded that the physiologic and noise data collected was of sufficient quality and quantity to examine the effects of night-time aircraft noise on sleep. There were some technical issues and loss of data but in general the design was successful. Data was collected for 87% of all study nights. The authors suggest that a larger study on a more national level could be feasibly conducted using this protocol, with participants experiencing different patterns of nocturnal aircraft noise.

In 2020, DEFRA commissioned a report by van Kamp et al, from the National Institute for Public Health and the Environment (RIVM) in the Netherlands. The review related to evidence on environmental noise exposure and annoyance, sleep disturbance, cardiovascular and metabolic health outcomes.

RIVM investigated whether there is sufficient new evidence since publication of the 2018 WHO reviews, to update the literature that informs UK policy. Since the systematic reviews that informed the WHO Guidelines were conducted in 2014, there have been more high-quality studies published. The WHO did not cover all the sources relevant within the scope of the IGCB(N), which include, in addition to transport and wind turbine noise, industrial noise, neighbourhood and neighbour noise, and low frequency noise from building services. Defra commissioned the RIVM to advise them of any updates to the evidence base which may impact their current recommendations.

For environmental noise (road, rail, aircraft and wind turbine noise sources) in relation to annoyance and sleep disturbance, the selection process resulted in 25 studies on road traffic, 20 on aircraft noise, 14 on railway noise and 11 on wind turbine noise. For sleep disturbance, the overall results were not consistent with each other. Twelve of the studies were on aircraft noise, ten on road traffic noise and six on railway noise.

The outcomes of the review revealed that for aircraft noise, new evidence from the DEBATS (France) and NORAH study (Germany) in relation to sleep disturbance suggest an update. This could also be considered for road and rail traffic noise, although for these sources no large differences are to be expected as far as annoyance reactions are concerned. A separate meta-analysis on the objective measures is suggested. The new studies also provide more evidence on the role of the number of events and the  $L_{max}$  levels and it would be worthwhile comparing the outcomes from the different new studies including the different noise indicators.

For annoyance, thirteen of the studies were related to aircraft noise, ten to road traffic noise and eight to railway noise. As with sleep disturbance, in terms of aircraft noise the DEBATS and NORAH studies offer updated results.

For environmental noise (from road, rail and air traffic, and wind turbines) in relation to cardiovascular and metabolic effects, 26 new studies were selected to be included in the review, with eight updated studies.

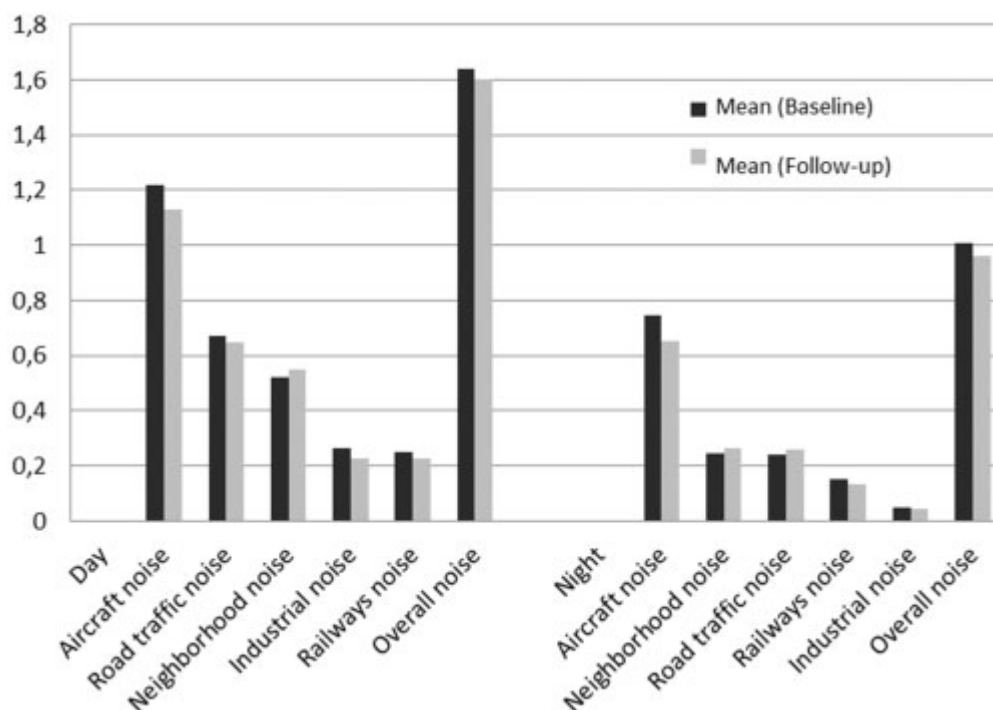
In conclusion, the RIVM report makes the following suggestions: Advocating for the IGCB(N) to consider taking the new evidence into account where appropriate.

- New meta-analyses could be conducted over a range of noise sources and effects.
- For annoyance, meta-analysis for all noise sources is possible. For aircraft noise-induced annoyance, due to the debate surrounding the selection of studies included in the WHO meta-analysis, consideration of the review and its consequences is suggested.
- For sleep-related effects, a meta-analysis for all transport sources is possible.
- For cardiovascular effects, all outcomes for some transport sources could be updated.
- New evidence warrants a meta-analysis for diabetes associated with road traffic and aircraft noise.

Beutel et al (2020) conducted a study that examined whether the effects of noise annoyance could be associated with depression, anxiety and sleep disturbance five years later. The study aimed to investigate any long-term effects of noise and associated annoyance, on mental health.

The authors investigated longitudinal data of over 11,900 participants of the Gutenberg Health Study, a population-based, prospective, single-centre cohort study in mid-Germany (age at baseline 35-74 years). Noise annoyance from aircraft, road traffic, railway noise, industrial noise and neighbourhood noise was assessed at baseline and again during a 5-year follow-up study. Annoyance was measured during the day and at night in each stage of the study. Depression, anxiety and sleep disturbance were assessed using the Patient Health Questionnaire and Generalised Anxiety Disorder Questionnaire.

Figure 12 displays the annoyance results, which indicated that overall noise annoyance remained stable over the 5-year period. There was a significant decrease in noise annoyance relating to aircraft over the 5 years, although aircraft noise annoyance was the most annoying source for day and night at each stage of the study. During the day, road traffic annoyance was the second most annoying source of noise, followed by neighbourhood, industrial and railway noise. At night, neighbourhood noise annoyance exceeded road traffic noise annoyance, and railway noise annoyance exceeded industrial noise annoyance. General noise annoyance remained stable throughout the study.



**Figure 12:** Mean noise annoyance by different sources at daytime and night time at baseline and follow-up.

The mental health results indicated that daytime noise annoyance predicted new onset of depressive, anxiety symptoms (also night-time annoyance) and sleep disturbance (beyond respective baseline scores). Additional predictors for this finding were being female, having a lower age and being of low socioeconomic status (SES). Night shift work was also associated with depression. Overall, baseline annoyance remained predictive of follow-up distress and sleep disturbances, even when follow-up annoyance was included in the regression model. Thus, long-term effects of annoyance on major mental health variables persisted. This applied to aircraft, neighbourhood and industrial noise annoyance. Noise annoyance baseline scores from specific sources (aircraft, neighbourhood, industrial) remained significant predictors of depression and anxiety, in addition to annoyance at follow-up.

The source-specific results indicated that daytime baseline aircraft annoyance predicted depression and anxiety. Sleep disturbance was most consistently predicted by neighbourhood annoyance (baseline and follow-up) and follow-up annoyance by aircraft (night) and road traffic (day and night).

## CHAPTER 8

# World Health Organisation (WHO) Guidelines 2018

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This chapter provides a brief overview of the recommendations made in the new WHO guidelines for road, rail and aircraft noise. These Guidelines are for the European region and were informed by a series of systematic literature reviews on each of the health outcomes concerned.

In 2010 the WHO was requested by Member States in the European Region to produce updated guidelines to their previously published Guidelines (1999 for annoyance, and 2009 for night noise). It was decided that alongside transportation noise, they should also include other noise sources that had not previously been formally considered such as electronic devices, wind turbines and toys.

The WHO Regional Office for Europe therefore developed environmental noise guidelines for the European Region, proposing an updated set of public health recommendations on exposure to environmental noise.

The main purpose of the guidelines is to provide recommendations for protecting human health from exposure to environmental noise originating from various sources: transportation (road traffic, railway and aircraft) noise, wind turbine noise and leisure noise.

One of the main outcomes of the systematic review are updated exposure response functions, for aircraft noise the key ones being the exposure response function for annoyance as a function of  $L_{den}$  and sleep disturbance versus  $L_{night}$ .

## Recommendations

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

For night noise exposure, the GDG strongly recommends reducing noise levels produced by aircraft during night-time to below 40 dB  $L_{night}$ , as aircraft noise above this level is associated with adverse effects on sleep.

It should be noted that, as there are usually fewer flights at night at an airport, more people are exposed to 45 dB  $L_{den}$  than 40 dB  $L_{night}$ . Therefore, the limiting guideline is the annoyance guideline, not the night-time guideline, despite the limit being 5 dB lower. To put this into context, in 2016 around Heathrow there were six million people who were exposed to 45 dB  $L_{den}$ , and two million exposed to 40 dB  $L_{night}$ .

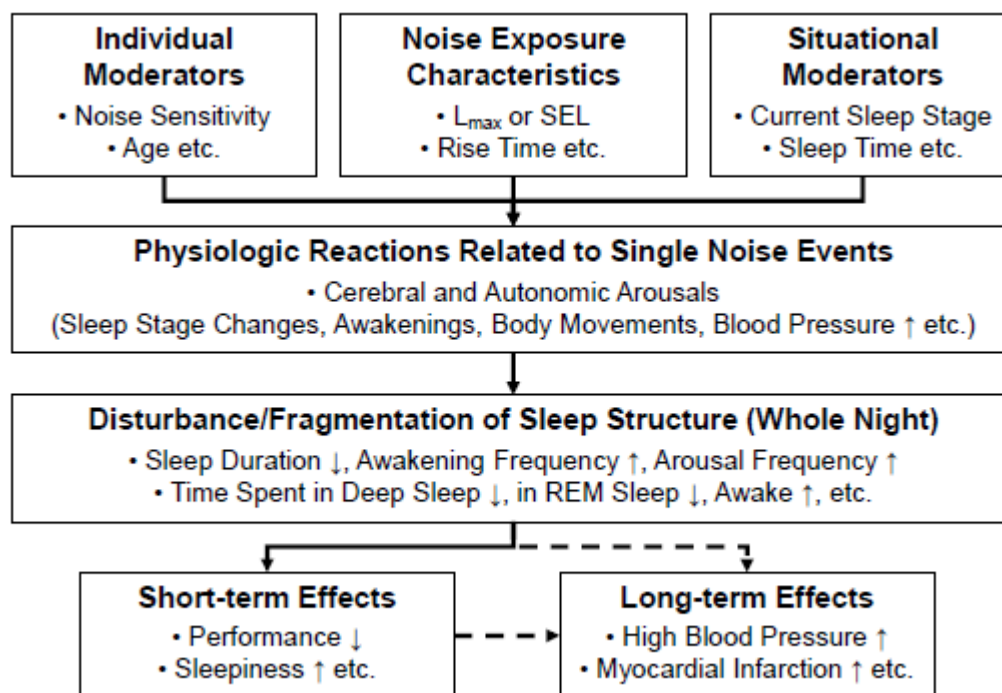
To reduce health effects, the GDG strongly recommends that policymakers implement suitable measures to reduce noise exposure from aircraft in the population exposed to

levels above the guideline values for average and night noise exposure. For specific interventions the GDG recommends implementing suitable changes in infrastructure.

Basner and McGuire authored the section on the Guidelines relating to sleep disturbance. Figure 13, reproduced from Basner and McGuire (2017) highlights the pathways by which sleep disturbance can result from aircraft noise. The effects on sleep are primarily determined by the number and acoustical properties (e.g., maximum SPL) of single noise events. The probability of noise disturbing sleep can also depend on situational factors such as depth of the current sleep phase, background noise level and individual (e.g., noise sensitivity) moderators.

In a normal night's sleep, the first half contains a higher amount of Slow Wave Sleep (SWS) or 'deep sleep' which is the most important for recovery and restoration, whereas the second half comprises more Rapid Eye Movement (REM) and lighter stages of sleep.

Repeated noise-induced arousals impair sleep quality and recuperation through changes in sleep structure including reduced sleep continuity, delayed sleep onset and early awakenings, less deep and REM sleep, and more time spent awake and in superficial sleep stages. Noise can also interfere with the process of falling back to sleep following a noise-induced awakening, thereby disrupting the important deeper stages of sleep.



**Figure 13:** The effects of noise on sleep (Basner and McGuire, 2017).

The focus of Basner and McGuire's review was to conduct a re-analysis of polysomnography measured awakenings, and a meta-analysis for self-reported sleep outcome measures, for road, rail, and aircraft noise.



The review assessed studies that included objective measurements of sleep using polysomnography<sup>2</sup>, considered to be the 'gold standard' of measurement. Four studies were identified on study selection for which the effects of road, rail, or aircraft noise on polysomnographically measured sleep were evaluated, although only two met the requirements for inclusion in the re-analysis.

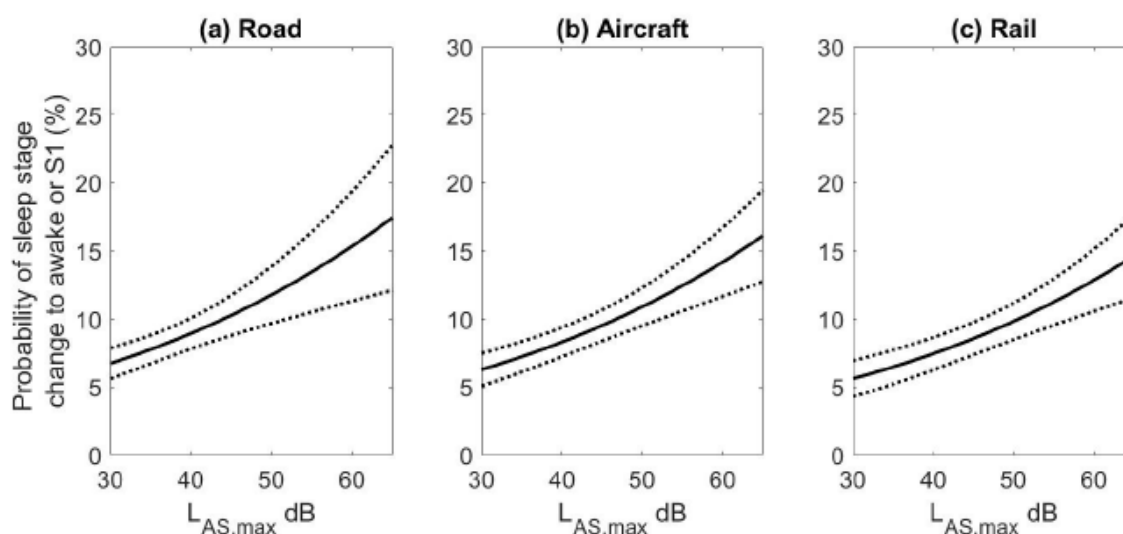
Single event-based analysis was completed in two studies conducted by the German Aerospace Center (DLR), both of which used similar methodology and were included in the re-analysis. The STRAIN study was conducted to investigate the effect of aircraft noise on sleep (Basner et al, 2006) The study was conducted between September 2001 and November 2002 and included 64 residents between the ages of 18 to 61 years (average age 38 years, 55% female) who lived around Cologne-Bonn Airport.

The DEUFRAKO study (a noise group comprising French and German researchers) was conducted to investigate the effect of rail noise on polysomnographically measured sleep (Elmenhorst et al, 2012). The study was conducted between February 2008 and July 2009 and included 33 individuals between the ages of 22 and 68 years (average age 36 years, 67% female) who lived near Cologne and Bonn close to railway lines. In both studies, subjects participated for nine consecutive nights and indoor noise levels were recorded in the bedroom. Physiological reactions to road traffic noise were also measured.

The raw data for these two datasets were obtained from DLR and used to derive exposure-response relationships for the probability of a sleep stage change to wake or S1; the STRAIN dataset was used for aircraft noise, the DEUFRAKO dataset was used for train noise, and the STRAIN and DEUFRAKO data were combined for road traffic noise. The three exposure-response curves for the undisturbed events are shown in Figure 14.

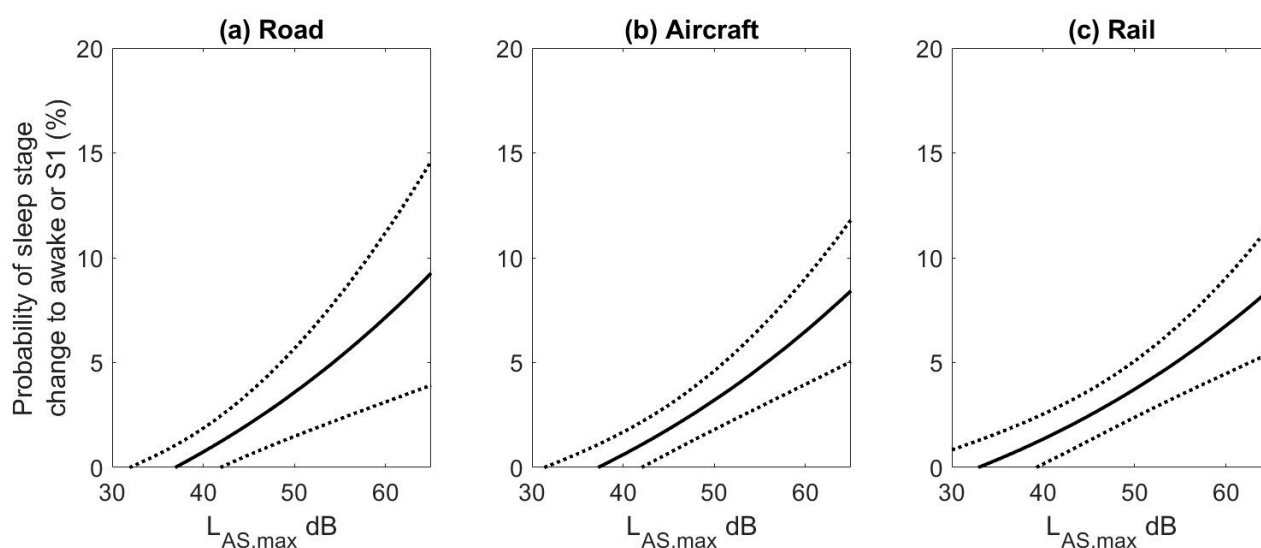
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<sup>2</sup> A group of recordings taken during sleep that shows brain wave changes, eye movements, breathing rate, blood pressure, heart rate, and the electrical activity of the heart and other muscles. Polysomnography is often used to determine sleep disorders.



**Figure 14:** Probability of a sleep stage change to awake or S1 in a 90 s time window following noise event onset depending on the maximum indoor sound pressure level ( $L_{AS,max}$ ) for (a) road (STRAIN and DEUFRAKO,  $N = 94$  subjects); (b) aircraft (STRAIN,  $N = 61$ ); and (c) rail noise (DEUFRAKO,  $N = 33$ ). 95% confidence intervals (dashed lines).

Spontaneous awakenings i.e., those not caused by an external stimulus occur normally in sleep. A healthy adult can experience up to twenty spontaneous awakenings per night. The probability of spontaneously awakening during the night was calculated separately for all three transportation sources using virtual events, as each subject was investigated for several nights, the other study nights could be used to determine spontaneous awakening probability. When spontaneous awakening probabilities were subtracted from the exposure-response curves, the exposure-response curves in Figure 15 were derived:



**Figure 15.** Probability of additional sleep stage changes to awake or S1 in a 90 s time window following noise event onset depending on the maximum indoor sound pressure level ( $L_{AS,max}$ ) for (a) road (STRAIN and DEUFRAKO,  $N = 94$  subjects); (b) aircraft

(STRAIN, N = 61); and (c) rail noise (DEUFRAKO, N = 33). 95% confidence intervals (dashed lines). Results are for the three unadjusted models.

The unadjusted odds ratio for the probability of awakening for a 10 dBA increase in the indoor  $L_{\max}$  was significant for aircraft (1.35; 95% CI 1.22–1.50), road (1.36; 95% CI 1.19–1.55), and rail (1.35; 95% CI 1.21–1.52) noise.

A meta-analysis of surveys linking road, rail, and aircraft noise exposure to self-reports of sleep disturbance was also conducted in this review. The meta-analyses resulted in 74 studies being included, from the year 2000 to 2015.

Results for all questions were averaged within each study, and the exposure-response relationships for the combined estimates are shown in Figure 15.

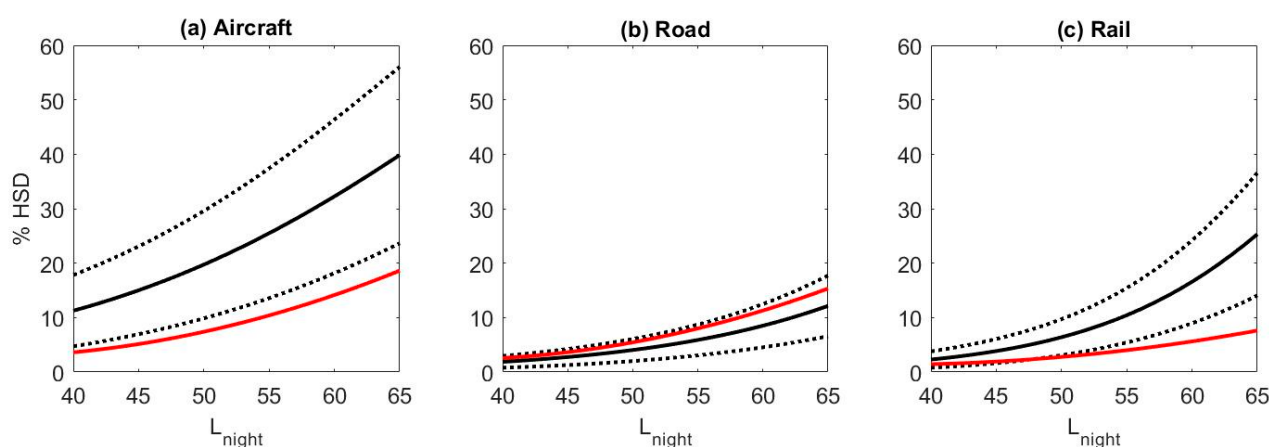
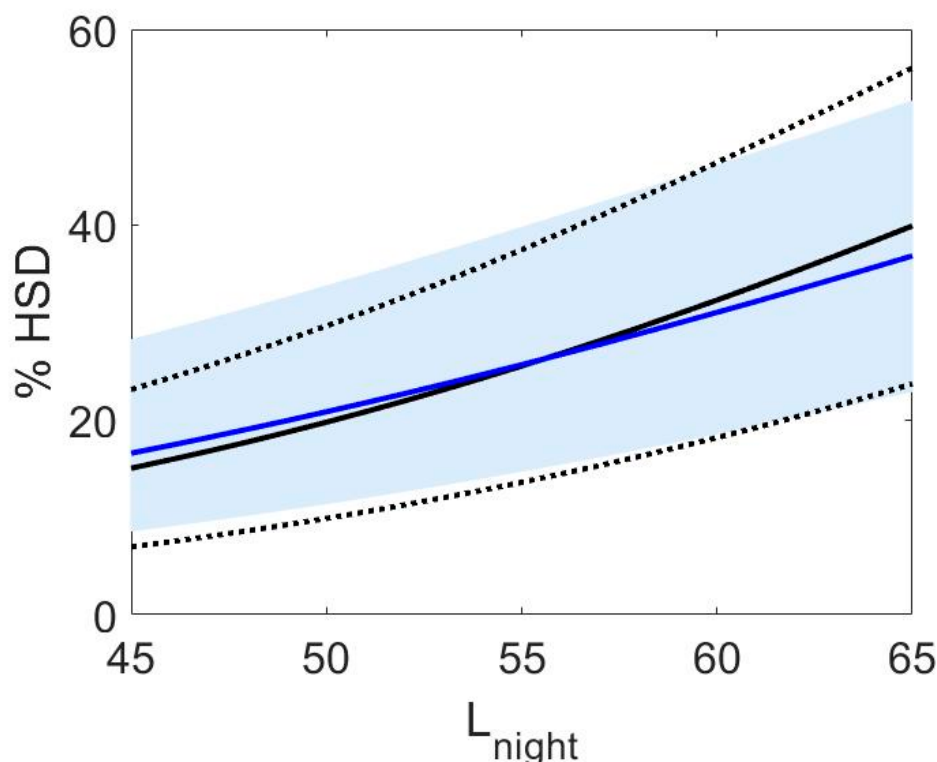


Figure 15: The percent highly sleep disturbed (HSD) based on responses to questions on awakenings, difficulty falling asleep, and sleep disturbance for road, rail, and aircraft noise (black dashed lines: 95% confidence intervals). Red = Miedema and Vos (2007) highly sleep disturbed exposure-response curves.

Janssen and Vos (2009) derived an updated exposure response curve for the percent highly sleep disturbed for aircraft noise only. This update included studies used by Miedema and Vos that were conducted in the year 1996 or later, and 4 additional studies, two of which are included in the review by Basner and McGuire. The aircraft noise exposure-response relationship developed in this analysis and the one derived by Janssen and Vos is shown in Figure 16:



**Figure 16:** The percent highly sleep disturbed (HSD) based on responses to questions on awakenings, difficulty falling asleep, and sleep disturbance for aircraft noise (black dashed lines: 95% confidence intervals). Blue = Janssen and Vos (2009) highly sleep disturbed exposure-response curve.

The odds ratios for sleep disturbance were calculated separately for those studies that did and did not ask about sleep disturbance, awakenings, or problems falling asleep relative to a specific noise-source. The odds ratios calculated for all noise sources and sleep outcomes were greater than 1 but not statistically significant when the noise source was not specifically mentioned in the question, except in one case. However, odds ratios were much higher and mostly statistically significantly different from 1 when the noise source was mentioned in the question. Basner and McGuire explain that this difference could be due to lack of adjustment for confounding factors in the analysis, such as age, gender, socio-economic status, and pre-existing sleep or health conditions.

The odds ratio for the percent highly sleep disturbed for a 10 dB increase in  $L_{\text{night}}$  was significant for aircraft (1.94; 95% CI 1.61–2.30), road (2.13; 95% CI 1.82–2.48), and rail (3.06; 95% CI 2.38–3.93) noise when the question referred to noise, but non-significant for aircraft (1.17; 95% CI 0.54–2.53), road (1.09; 95% CI 0.94–1.27), and rail (1.27; 95% CI 0.89–1.81) noise when the question did not refer to noise.

## CHAPTER 9

# Survey of Noise Attitudes (SoNA) 2014

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## CAP 2161

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The Survey of Noise Attitudes (SoNA) study was commissioned by the Department for Transport to obtain new and updated evidence on attitudes to aviation noise around airports in England (SoNA 2014).

The main focus of the SoNA 2014 study was on annoyance responses and general attitudes to aircraft noise. These were reported in CAP 1506<sup>3</sup> However, there was also a subset of questions relating to self-reported sleep disturbance and night noise from aircraft. The overall aims of the SoNA 2014 Sleep Disturbance analysis were to:

- Explore relationships between self-reported sleep disturbance and noise exposure.
- Explore any potential relationship between self-reported sleep disturbance and self-reported quality of health.

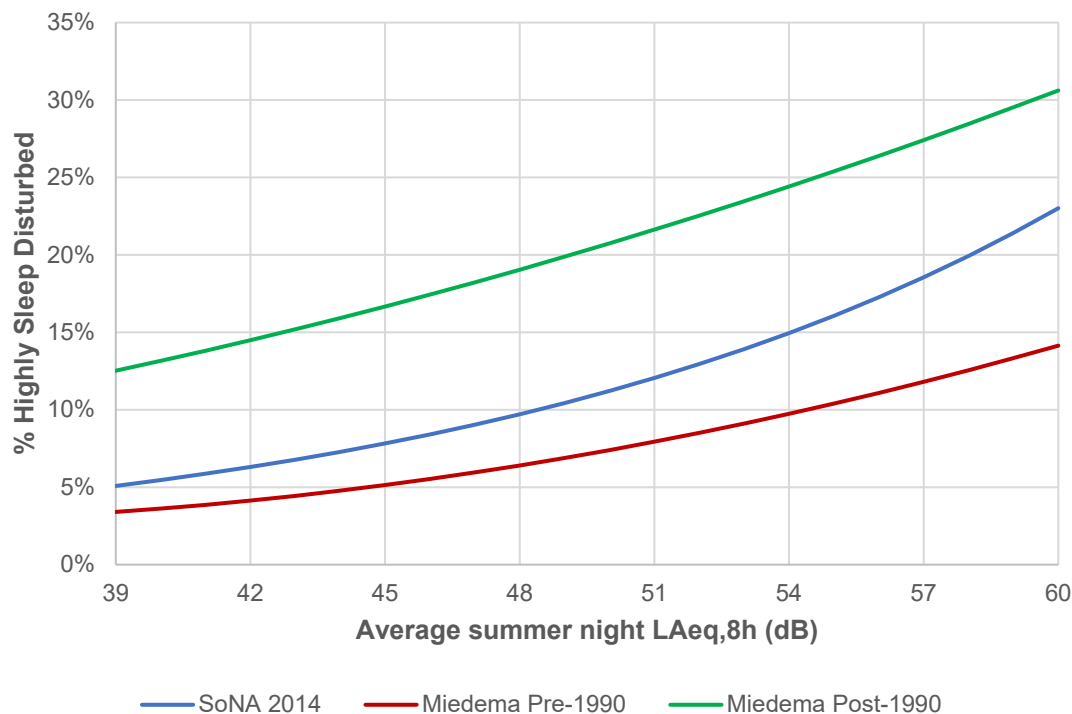
This report assesses attitudes to night-time aircraft noise, using a sample of the SoNA 2014 survey data set. The SoNA 2014 data set contained responses from 1,999 residents around eight airports in England. Respondents were selected using a random, partially-clustered approach. For the purposes of analysing attitudes to night-time aircraft noise, the SoNA 2014 dataset was restricted to respondents from around three airports in England: Gatwick, Heathrow and Stansted, totalling 1,588 participants. 100 of these were not resident during summer 2014, leaving a sample of 1,488, five of which did not answer the night-time annoyance question leaving 1,483 valid responses. Their average summer night  $L_{Aeq,8h}$  noise exposure ranged from below 39 dB to greater than 54 dB.

Unlike for daytime annoyance, there is no standardised question from which to obtain views on self-reported sleep disturbance. Therefore, views were obtained using the standardised annoyance question, 'to what extent are you bothered, disturbed or annoyed' by noise from aeroplanes during the night (11pm-7pm)?'. Responses were recorded on a 5-point categorical scale. The results are summarised below:

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<sup>3</sup> Survey of Noise Attitudes 2014: Aircraft. CAP 1506 (2017) Civil Aviation Authority.  
<http://publicapps.caa.co.uk/modalapplication.aspx?appid=11&mode=detail&id=7744>

- The exploratory analysis compared reported mean night-time disturbance scores against average night noise exposure defined using three different noise indicators: average summer night  $L_{Aeq,8h}$ , annual average night  $L_{night}$ , and average summer night N60. The results revealed that there is insufficient evidence to change from the current practice of using average summer night  $L_{Aeq,8h}$  noise exposure for UK assessments.
- Mean disturbance score and the likelihood of being highly sleep disturbed were found to increase with increasing night-time noise exposure ( $L_{Aeq,8h}$ ). The relationship found was close to linear, though disturbance levels plateau at low and high exposure.
- For a given noise exposure, a higher proportion of respondents was found to be highly sleep disturbed compared with the Miedema pre-1990 dose-response function. At 45 dB  $L_{Aeq,8h}$ , 8-10% were estimated to be highly sleep disturbed compared with 5% for the Miedema curve. At 48 dB  $L_{Aeq,8h}$ , 10-12% were estimated to be highly sleep disturbed compared with 6% for the Miedema curve. The SoNA 2014 night-time dose response function was, however, found to be lower than the Miedema function from the post-1990 studies. This is shown in Figure 17.
- Noise exposure and self-reported sleep disturbance were compared against the self-reported health rating (5-point scale) and the Short Warwick-Edinburgh Mental Wellbeing Scale (SWEMWBS), a measure of well-being. Poorer health ratings and lower SWEMWBS scores were found to be associated with sleep disturbance, but not with noise exposure.



**Figure 17:** Logistic regression function for percent highly sleep disturbed for SoNA 2014 night as a function of average annual  $L_{night}$  and compared with Miedema pre-1990 and post-1990 studies<sup>4</sup>.

## SoNA Sleep: Further Analysis

This report focusses on further examination of the sleep disturbance element of the SoNA study and examines the use of additional aircraft noise-induced awakenings as the noise dose function, instead of the  $L_{Aeq,8h}$  and  $L_{night}$  metrics that were investigated in the SoNA Sleep report.

The overall aims of the SoNA 2014 ‘Sleep Study: Further Analysis’ were to:

- Investigate alternative night noise metrics such as additional aircraft noise-induced awakenings.
- Explore the correlation between the number of additional aircraft noise-induced awakenings and average night noise exposure.
- Explore any potential relationship between additional aircraft noise-induced awakenings and self-reported quality of health.

<sup>4</sup> Miedema, H. M. E., Vos, H. (2007) Associations between self-reported sleep disturbance and environmental noise based on reanalyses of pooled data from 24 studies. *Behavioural Sleep Medicine*, 5(1), 1-20.

- Examine any link between self-reported noise sensitivity and the number of additional aircraft noise-induced awakenings at night from aircraft noise.

CAP 2161 used average 8-hour night noise exposure as the noise dose in order to investigate associations with self-reported sleep disturbance. Despite the average night 8-hour noise dose being correlated with the number and levels of single aircraft noise events, communities have expressed concern that average 8-hour noise doses do not adequately reflect the night-time disturbance they experience.

Individuals experience different numbers of different single event noise levels, depending on their geographic location relative to a given airport and the mix of aeroplanes operating at night.

Basner et al performed extensive laboratory and field studies on the effects of aircraft noise on sleep between 1999 and 2004. The study utilised polysomnographic measurement of sleep patterns. Polysomnography is made up of several discrete measurements of brain and body functions. It includes the electroencephalogram (EEG), which measures brain electrical activity, the electrooculogram (EOG), which measures eye movement, the electromyogram (EMG) that measures muscle tension, and the electrocardiogram (ECG) that measures heart activity. Together, the EEG, EOG, and EMG signals are called polysomnography, from which the five different sleep stages may be classified.

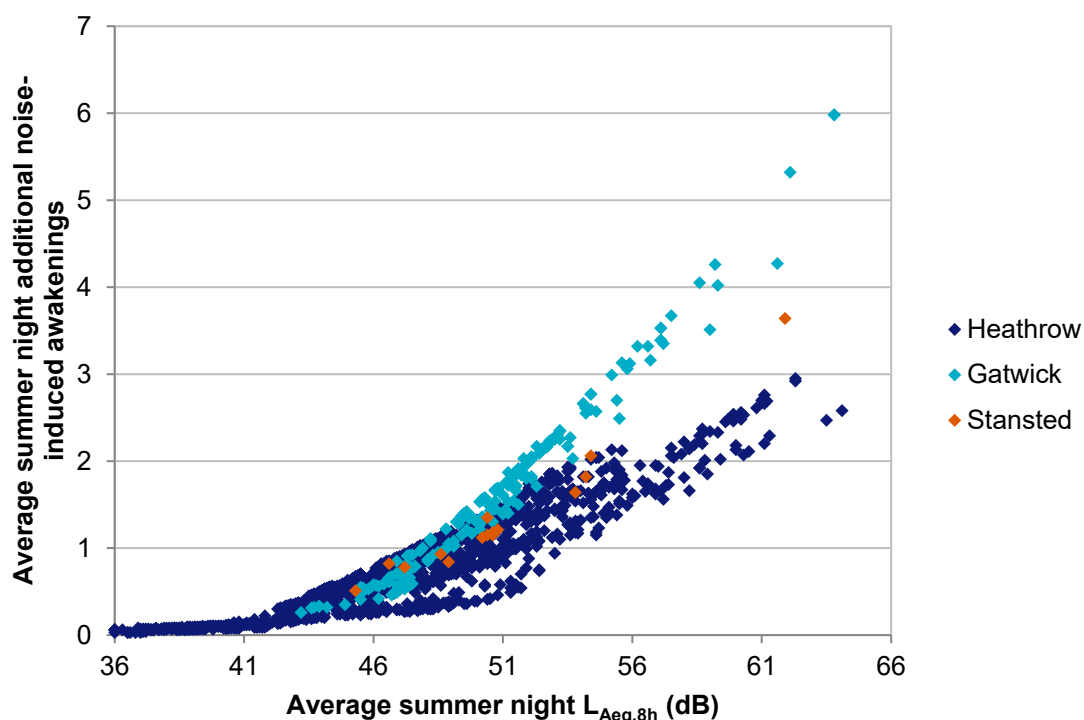
Basner et al defined awakenings as EEG and EMG activations that last for at least 15 seconds. In the study, subjects on average, experienced about 24 awakenings per night regardless of any noise stimulus, with the majority lasting for between 15 and 45 seconds, which were too short to be remembered the next day. However, one or more of the awakenings may have lasted longer and may have been associated with waking consciousness and may have been recalled the next day.

Basner et al then related awakening to indoor aircraft noise levels and found that the probability of additional noise-induced awakening (PAWR) increased with increased indoor maximum noise level and produced an equation to predict the probability of additional noise-induced awakening at a given respondent location. The probability of additional aircraft noise-induced awakenings (PAWR) is related to a maximum noise level of each aircraft event, rather than the 8-hour average night noise exposure.

Using the Basner relationship reveals that the distribution of single event level and number of events at a given location can be distilled down to a single value of the number of additional awakening additional noise-induced awakenings.

The number of additional aircraft noise-induced awakenings for each respondent was correlated with the average summer night  $L_{Aeq,8h}$  dB noise level, and is shown as a scatterplot in Figure 18.

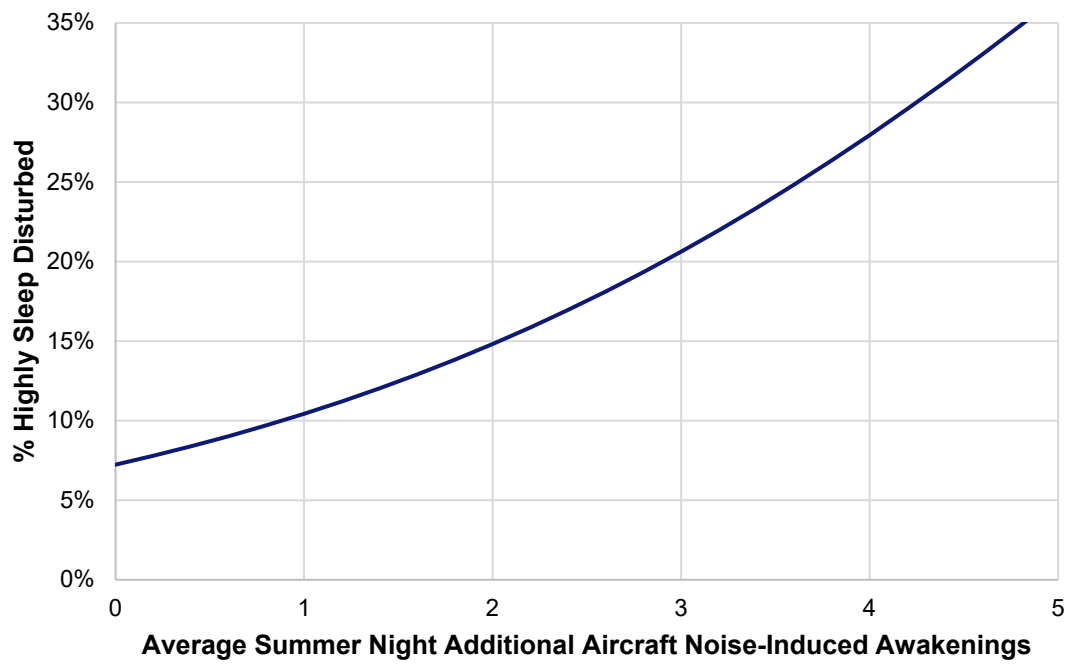




**Figure 18:** Association between average summer night  $L_{Aeq,8h}$  noise level and the number of additional aircraft noise-induced awakenings for Gatwick, Heathrow and Stansted airports.

The number of additional aircraft noise-induced awakenings was compared with the average summer night  $L_{Aeq,8h}$  noise dose. As confirmed by Basner, whilst there is a clear correlation between the two measures, the additional aircraft noise-induced awakenings indicator gives more weight to the number of events. Therefore, areas experiencing fewer, but louder, events show comparatively fewer awakenings than areas experiencing more less noisy events, and fewer awakenings than the average summer  $L_{Aeq,8h}$  noise dose might indicate.

The SoNA 2014 survey data was then used to determine the association between the number of additional aircraft noise-induced awakenings and the percentage of respondents highly sleep disturbed. One additional night awakening was found to associate with 10% of respondents being highly sleep disturbed. Two and three additional aircraft noise-induced awakenings per average summer night associated with 15% and just over 20% of respondents highly sleep disturbed respectively (Figure 19).



**Figure 19:** Logistic regression function for percent highly sleep disturbed for SoNA 2014 night as a function of average summer night additional aircraft noise-induced awakenings.

## CHAPTER 10

# Summary and Conclusions

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This report has provided an update on the findings in the field of aircraft noise and sleep disturbance between 2014-2022. Studies such as DEBATS, NORAH, SoNA Sleep and the updated WHO Guidelines for Europe have been included, as well as other published work such as results from the ANIMA project, TraNQuIL and SiRENE studies.

A common theme when discussing the future of aircraft noise and sleep disturbance studies is the importance of the standardisation and validation of questions on the effects of noise on sleep (in the same way the ICBEN annoyance questions are standardised) and improves the ability to compare results between studies. The use of more standardised general sleep disturbance questions is encouraged e.g., about insomnia symptoms and other questions that do not ask specifically about noise as the source of sleep disturbances. This is important for avoiding bias and for improving comparability with other risk factors for sleep disturbances.

The development of wearable sleep-recording devices has improved over recent years, which allows for much larger-scale data collection and may provide an opportunity to study other biological markers which may link noise exposure with sleep deprivation.

To date, the link between annoyance and sleep disturbance is still not well understood. It is not clear whether aircraft noise annoyance results in sleep disturbances, or whether sleep disturbance results in aircraft noise annoyance. It is possible that both directions are possible, and sleep disturbance due to aircraft noise can result in fatigue and tiredness in the daytime, which may result in annoyance. Conversely, if a person experiences annoyance due to aircraft noise during the day, this may affect the ability to experience good quality sleep and result in a higher probability of being woken by aircraft noise during the night. This issue requires long-term study, which would also assist in the understanding of how sleep disturbance is linked to the development of health outcomes such as cardiovascular disease.

As described in the ANIMA publication (Bartels, 2022) further research is needed into aircraft noise-induced sleep disturbance and age, in particular the elderly population. Although there has been an increase in the study of sleep disturbance in children, little is known on the impact to the older population. Similarly, more research is needed on the influence of noise sensitivity, which is known to be an important non-acoustic factor for noise annoyance and sleep disturbance. There is the possibility for attitudes towards aircraft noise to influence results from both self-reported and objectively measured sleep disturbance research.

In conclusion, the area of aircraft noise and sleep disturbance continues to grow and there is much scope for further investigation into the mechanisms of how aircraft noise impacts such a fundamental and necessary part of life. In addition, it is expected that with the development of various types of drones, electric vertical take-off and landing (eVTOL) vehicles and super-sonic aircraft, such emerging noise sources will change the acoustical characteristics of noise in the skies, and there is a need for future research in this area, including the need to understand the impact such emerging technologies will have on the sleep of exposed populations.

## CHAPTER 11

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