WHITE PAPER ON AIRCRAFT NOISE* AVIATION NOISE IMPACTS: STATE OF THE SCIENCE

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Noise is defined as "unwanted sound". Aircraft noise is one, if not the most detrimental environmental effect of aviation. It can cause community annoyance, disrupt sleep, adversely affect academic performance of children, and could increase the risk for cardiovascular disease of people living in the vicinity of airports. In some airports, noise constrains air traffic growth. This white paper summarizes the state of the science of noise effects research in the areas noise measurement and prediction, community annoyance, children's learning, sleep disturbance, and health.

Introduction

Purpose: The goal of this paper is to briefly summarize the current state of scientific knowledge regarding the adverse effects of aircraft noise emissions on the public. Every effort has been made to base the findings upon peer-reviewed publications, carefully reviewed by specialists from around the world. The topics addressed here are community annoyance, children's learning, sleep disturbance, health impacts, and the noise of supersonic aircraft. This white paper also provides some background information on noise measurement and prediction, as well as technical definitions for the interested reader.

Task of the panel: Aircraft noise discussions can be very emotional, and politicians and legislators often struggle to define limit values that both protect the population against the adverse effects of aircraft noise but do not restrict the positive societal effects of air traffic. Noise effects researchers have an important advisory role. They derive so-called exposure-response functions that allow health impact assessments and therefore inform political decision-making. The efforts of the Noise Panel were directed at assessing the current state of the science and provide contracting states with a brief overview of the impacts of aircraft noise on communities. This white paper constitutes a consensus among its authors who have considerable experience in noise effects research, and is based on input from an international expert panel workshop held on February 10 and 11, 2015 in Alexandria, VA, USA. Noise effects depend, among others, on housing structure and cultural values, and legislation and limit values accordingly differ considerably between contracting states. Therefore, the authors did not try to suggest specific limit values, but rather pointed to existing exposure-response functions and recommendations of international organizations.

Community Annoyance

Definition of community annoyance: Community annoyance refers to the average evaluation of the disturbing aspects or nuisance of a noise situation by a "community" or group of residents, combined in a single outcome, annoyance. To facilitate inter-study comparisons and data pooling for the development of exposure-response relationships, a standardized annoyance question has been proposed by members of the International Commission on Biological Effects of Noise (ICBEN),[1] and was adopted by ISO TS 15666.[2] The percentage of highly annoyed respondents is considered to be the main indicator of community annoyance. The use of a common question allows for the comparison of studies from around the globe. As such, the ISG encourages States to utilize the ISO TS 15666 survey in their efforts to measure and understand community annoyance.

Moderating non-acoustic variables: Individual annoyance scores are not only related to acoustic variables, but can be importantly moderated by several personal and situational variables. Two meta-analyses on the influence of such non-acoustical factors on annoyance showed the largest effects of age, fear and noise sensitivity.[3,4] Additional moderating variables put forward are beliefs on the necessity of the noise source, the ability to somehow control or cope with noise or its consequences, trust in authorities, and previous experience with or future expectations regarding noise.[5,6]

Exposure-response relationships: Over the years, several attempts have been made to relate the percentage of respondents highly annoyed by a given source to the noise exposure level in LDN. The derivation of exposure-response curves based on data from many individual studies[7] yielded different curves for aircraft, road traffic, and railway noise, with higher annoyance for aircraft noise than for road traffic or railway noise at the same exposure level. However, there is evidence that the annoyance response to aircraft noise has even increased over the years, and that exposure-response curves based on older aircraft noise annoyance data may no longer apply.[8,9] This stresses the need for an update based on more recent studies using standardized methods.

(Inter)national versus local exposure-response relationships: While exposure-response relationships have been recommended for assessing the expected annoyance response in noise situations, they are not applicable to assess the short-term effects of a change in noise climate. There are indications for an temporary overshoot in annoyance response in situations with a high rate of change, for instance where a new runway was opened.[10,11] Also in more or less steady state situations, the annoyance response in specific surveys often differs from the average expected response.[12] Since airports and communities may differ greatly in several variables moderating annoyance, local exposure-response relationships, if available, may be preferred for predicting annoyance. Still, exposure-response relationships describing the average annoyance response are required to allow health impact assessment across communities and to establish preferable limit values for levels of aircraft noise.

Complaints and their relationship to noise and noise effects: Many airports receive and log complaints as part of their noise monitoring and community outreach efforts. Complaints seem to be triggered by unusual events (e.g. louder than normal; unusual aircraft ground track or altitude) and operational changes (changes in runway usage or flight tracks). Annoyance and complaints are different phenomena, the first being a privately held opinion, and the latter being an overt action. Relatively few studies have utilized complaints databases to investigate whether complaints are related to long-term annoyance as measured using social surveys. Rather than monitoring the number of callers, which may be distorted by repeat callers, this approach should preferably be based on the number of individual complainants and the number of specific issues or incidents that cause complaints There is, however, evidence to suggest that complainants do not represent a cross-section of the population at large, both in terms of their demographic characteristics and their annoyance.

Supplementary noise metrics: An important question for aircraft noise annoyance is whether the annoyance due to infrequent high levels of noise events is the same as the annoyance caused by frequent moderate levels at the same LDN. While some data suggest that the trade-off between levels and numbers of overflights in LAeq-based metrics such as LDN is approximately correct for predicting noise annoyance,[13] there is also data suggesting that a higher weight of the number of flights might be appropriate.[14] However, an examination of 10+ airport surveys did not support a weighting of "number" greater than that implicit in LAeq.[15] On average, the weighting was less than that.

Noise mitigation: Annoyance due to aircraft noise has been recognized by authorities and policy makers as a harmful effect that should be prevented and reduced. Priority is given to noise reduction at the source (e.g., engine noise, aerodynamic noise) and reducing noise by adjusting take-off and landing procedures, but these measures are not always sufficient or feasible. Sound insulation of dwellings is often applied, but may not reduce annoyance levels when it is associated with poor indoor air quality.[16] In addition, the observed influence on annoyance of several non-acoustical factors such as fear, perceived control and trust in authorities suggests that communication strategies addressing these issues could strongly contribute to the reduction of annoyance, alongside or even in the absence of a noise reduction.

Conclusions: There is substantial evidence that aircraft noise exposure is associated with annoyance indicators, and exposure-response relationships have been derived to estimate the expected percentage of highly annoyed persons at a community level. Still, several personal and situational factors importantly affect the annoyance of individuals. Recent evidence for an increase in the annoyance response at a given exposure level indicates the need for updating exposure-response curves based on recent studies using harmonized methods, as well as verifying the circumstances leading to a heightened community response. This could inform political decision making on managing aircraft noise exposure and on mitigation measures.

Children's Learning

Chronic aircraft noise exposure and children's learning: Recent reviews of how noise, and in particular aircraft noise, affect children's learning have concluded that aircraft noise exposure at school or at home is associated with children having poorer reading and memory skills.[17] There is also an increasing evidence base which suggests that children exposed to chronic aircraft noise at school have poorer performance on standardized achievement tests, compared with children who are not exposed to aircraft noise. In the limited space available here it is only possible to discuss some of the central epidemiological field studies forming the empirical basis of these conclusions. The most recent large scale cross-sectional study, the RANCH study (Road traffic and Aircraft Noise and children's Cognition & Health), of 2844 9-10 year old children from 89 schools around London Heathrow, Amsterdam Schiphol, and Madrid Barajas airports found exposure-response associations between aircraft noise and poorer reading comprehension and poorer recognition memory, after taking social position and road traffic noise, into account.[18] Reading comprehension began to fall below average at around 55dB L_{Aeq},16hours at school but as the association was linear, there is no specific threshold above which noise effects begin, and any reduction in aircraft noise exposure should lead to an improvement in reading comprehension. A 5dB increase in aircraft noise exposure was associated with a 2 month delay in reading age in the UK, and a 1 month delay in the Netherlands.[19] These associations were not explained by air pollution.[20] Children's aircraft noise exposure at school and at home are often highly correlated. In the RANCH study, night-time aircraft noise at the child's home was also associated with impaired reading comprehension and recognition memory, but night-noise did not have an additional effect to that of daytime noise exposure on reading comprehension or recognition memory.[21]

Interventions to reduce aircraft noise exposure at school: Studies have shown that interventions to reduce aircraft noise exposure at school do improve children's learning outcomes. The longitudinal, prospective Munich Airport study[22] found that prior to the relocation of the airport in Munich, high noise exposure was associated with poorer long-term memory and reading comprehension in children aged 10 years. Two years after the airport closed these cognitive impairments were no longer present, suggesting that the effects of aircraft noise on cognitive performance may be reversible if the noise stops. In the cohort of children living near the newly opened Munich airport impairments in memory and reading developed over the two-year period. This study suggests that it takes a couple of years for impairments to develop. A cross-sectional study of 6,000 schools exposed between the years 2000-2009 at the top 46 United States airports (exposed to Day-Night-Average Sound Level of 55 dB or higher) found significant associations between aircraft noise and standardized tests of mathematics and reading, after taking demographic and school factors into account.[23] In a sub-sample of 119 schools, it was found that the effect of aircraft noise on children's learning disappeared once the school had sound insulation installed. These studies suggest that insulation of schools yields improvements in children's learning.

Mechanisms linking chronic aircraft noise exposure and learning: Aircraft noise may directly affect the development of cognitive skills such as reading and memory but a range of pathways and mechanisms for the effects have also been proposed. Effects might be accounted for by communication difficulties, teacher and pupil frustration, reduced morale, impaired attention, increased arousal – which influences task performance, and sleep disturbance from home exposure which might cause performance effects the next day.[24,25] Noise causes annoyance, particularly if an individual feels their activities are being disturbed or if it causes difficulties with communication. In some individuals, annoyance responses may result in physiological and psychological stress responses, which might explain poorer learning outcomes.

Guidelines for children's noise exposure at school: The WHO Community Noise Guidelines[26] suggest that the background sound pressure level in school classrooms should not exceed L_{Aeq} 35dB during teaching sessions to protect from speech intelligibility and disturbance of information extraction. The WHO guidelines also suggest that school playgrounds outdoors should not exceed 55dB L_{Aeq} during the recess period, to protect from annoyance. The American National Standards Institute (ANSI) Standard for School Acoustics (ANSI S12.50-2002/2010), suggests that internal background noise for unoccupied classrooms should be 35dB L_{Aeq}. The ANSI standard is supported by the Acoustical Society of America and INCE-USA. While the WHO and the ANSI guidelines both specify a maximum sound level of 35 dB for classrooms, it should be noted that for ANSI guidelines this is for unoccupied classrooms, while for the WHO guidelines this is for occupied classrooms. It should also be noted that WHO included cognitive impairment of children as one end-point in their publication on *Burden of Disease from Environmental Noise - Quantification of healthy life years lost in Europe,*[27] relying mainly on the results from the Munich study and the RANCH study.

Conclusions: There is sufficient evidence for a negative effect of aircraft noise exposure on children's cognitive skills such as reading and memory, as well as on standardized academic test scores. Evidence is also emerging to support the insulation of schools that may be exposed to high levels of aircraft noise. A range of plausible mechanisms have been proposed to account for aircraft noise effects on children's learning. Further knowledge about exposure-effect relationships in different contexts would further inform decision-making. It may also be informative to derive relationships for a range of additional noise exposure metrics, such as the number of noise events. To date, few studies have evaluated the effects of persistent aircraft noise exposure throughout the child's education and there remains a need for longitudinal studies of aircraft noise exposure at school and educational outcomes.

Sleep Disturbance

Sleep and its importance for health: Sleep is a biological imperative and a very active process that serves several vital functions. Undisturbed sleep of sufficient length is essential for daytime alertness and performance, quality of life, and health.[27,28] The epidemiologic evidence that chronically disturbed or curtailed sleep is associated with negative health outcomes (like obesity, diabetes, and high blood pressure) is overwhelming. For these reasons, noise-induced sleep disturbance is considered the most deleterious non-auditory effect of environmental noise exposure.

Aircraft noise effects on sleep: The auditory system has a watchman function and constantly scans the environment for potential threats. Humans perceive, evaluate and react to environmental sounds while asleep.[29] At the same SPL, meaningful or potentially harmful noise events are more likely to cause arousals from sleep than less meaningful events. As aircraft noise is intermitted noise, its effects on sleep are primarily determined by the number and acoustical properties (e.g., maximum SPL, spectral composition) of single noise events. However, whether or not noise will disturb sleep also depends on situational (e.g., sleep depth[30]) and individual (e.g., noise sensitivity) moderators.[29] Sensitivity to nocturnal noise exposure varies considerably between individuals. The elderly, children, shift-workers, and those at ill health are considered at risk for noise-induced sleep disturbance.[28] Repeated noise-induced arousals impair sleep quality through changes in sleep structure including delayed sleep onset and early awakenings, less deep (slow wave) and rapid eye movement (REM) sleep, and more time spent awake and in superficial sleep stages.[30,31]

ENREF_2 Deep and REM sleep have been shown to be important for sleep recuperation in general and memory consolidation specifically. Non-acoustic factors (e.g., high temperature, nightmares) can also disturb sleep and complicate the unequivocal attribution of arousals to noise.[32] Field studies in the vicinity of airports have shown that most arousals cannot be attributed to aircraft noise, and noise-induced sleep-disturbance is in general less severe than that observed in clinical sleep disorders like obstructive sleep apnea.[33] Short-term effects of noise-induced sleep disturbance include impaired mood, subjectively and objectively increased daytime sleepiness, and impaired cognitive performance.[34,35] It is hypothesized that noise-induced sleep disturbance contributes to the increased risk of cardiovascular disease if individuals are exposed to relevant noise levels over months and years. Recent epidemiologic studies indicate that nocturnal noise exposure may be more relevant for long-term health consequences than daytime noise exposure, probably also because people are at home more consistently during the night.[36]

Noise effects assessment: Exposure-response functions relating a noise indicator (e.g., maximum SPL) to a sleep outcome (e.g. awakening probability) can be used for health impact assessments and inform political decision-making. Subjects exposed to noise typically habituate, and exposure-response functions derived in the field (where subjects have often been exposed to the noise for many years) are much shallower than those derived in unfamiliar laboratory settings.[37,38] Unfortunately, sample sizes and response rates of the studies that are the basis for exposure-response relationships were usually low, which restricts generalizability. Exposure-response functions are typically sigmoidal (s-shaped) and show monotonically increasing effects. Maximum SPLs as low as 33 dB(A) induce physiological reactions during sleep, i.e., once the organism is able to differentiate a noise event from the background, physiologic reactions can be expected (albeit with a low probability at low noise levels).[37] This reaction threshold should not be confused with limit values used in legislative and policy settings, which are usually considerably higher. At the same maximum SPL, aircraft noise has been shown to be less likely to disturb sleep compared to road and rail traffic noise, which was partly explained by the frequency distribution, duration, and rise time of the noise events[31,39] Although equivalent noise levels are correlated with sleep disturbance, there is general agreement that the number and acoustical properties of noise events better reflect the degree of sleep disturbance (especially for intermitted aircraft noise). As exposure-response functions are typically without a clearly discernible sudden increase in sleep disturbance at a specific noise level, defining limit values is not straight forward and remains a political decision weighing the negative consequences of aircraft noise on sleep with the societal benefits of air traffic. Accordingly, nighttime noise legislation differs between contracting states.

Noise mitigation: Mitigating the effects of aircraft noise on sleep is a three-tiered approach. Noise reduction at the source has highest priority. However, as it will take years for new aircraft with reduced noise emissions to penetrate the market (and will thus not solve the problem in the foreseeable future), additional immediate measures are needed. For example, noise-reducing take-off and landing procedures can often be more easily implemented during the low-traffic nighttime. Land-use planning can be used to reduce the number of relevantly exposed subjects. Passive sound insulation (including ventilation) represent mitigation measures that can be effective in reducing sleep disturbance, as subjects usually spend their nights indoors. At some airports nocturnal traffic curfews have been imposed by regulation. They can be very effective, but are also a drastic measure and, according to ICAO's Balanced Approach, should only be implemented as a last resort. It is important to line up the curfew period with the (internationally varying) sleep patterns of the population.

Conclusions: Undisturbed sleep is a prerequisite for high daytime performance, well-being and health. Aircraft noise can disturb sleep and impair sleep recuperation. Further research is needed to (a) derive reliable exposure-response relationships between aircraft noise exposure and sleep disturbance, (b) explore the link between noise-induced sleep disturbance and long-term health consequences, (c) investigate vulnerable populations, and (d) demonstrate the effectiveness of noise mitigation strategies. This research will inform political decision-making and help mitigate the effects of aircraft noise on sleep.

Health Impacts

There are several ways in which noise could affect health,[40] including a physiological response via the autonomic nervous system leading to rises in blood pressure and heart rate, stress potentially mediated by annoyance, and disturbed sleep. However, the number of health studies available to date is limited.

Aircraft noise and cardiovascular disease (CVD) hospitalizations and mortality: Two large studies have found associations between aircraft noise and heart disease and stroke; one of these examined hospitalization rates in 6 million adults aged 65 years and over living near 89 US airports,[41] the second examined hospitalization and mortality in a population of 3.6 million potentially affected by noise from London Heathrow airport.[42] These studies used a small area (ecological) not individual-level design, so may not have fully accounted for confounding factors. Two individual-level studies have found associations between heart disease and stroke in subgroups who had lived in the same place for >15-20 years; one a cross-sectional study of approximately 5000 individuals living near seven European airports,[43] the second a census-based study of 4.6 million individuals in the Swiss National cohort.[44] A further two individual-level studies, of heart disease mortality in adults in Vancouver[45] and stroke mortality in 64,000 adults living in Denmark,[46] did not find associations possibly due to the fact that the study areas had low levels of noise.

Aircraft noise and hypertension: Two meta-analyses[47,48] relating to seven epidemiological studies in total have found associations between chronic aircraft noise exposure and hypertension in adults (meta-analyses combine evidence from several studies and are considered to provide the highest ranked research and to provide stronger evidence than single studies). Results from the meta-analyses are consistent with findings from meta-analyses of studies investigating road noise that have also shown associations with hypertension.[49] Aircraft noise has been associated but not consistently so with raised blood pressure in children in a number of studies, of which the largest involved 62 schools around London Heathrow and Schiphol airport.[50] The findings from epidemiological studies are supported by experimental and field studies that have demonstrated short-term effects of aircraft noise on blood pressure in adults. A field study of 140 individuals living near four European airports found increases in blood pressure measurements during the night sleeping period related to aircraft movements.[51] Short-term experimental studies in healthy adults[52] and those with existing cardiovascular disease[53] have found dose-response associations between aircraft noise at night and next-morning blood pressure and blood vessel functioning.

Aircraft noise and cardiovascular risk factors: Few studies have been conducted looking at cardiovascular risk factors e.g. biomarkers, adiposity and diabetes. Two experimental studies of aircraft noise recordings played at different volumes during sleep did not find associations with inflammatory markers (Interleukin-6, C-Reactive Protein) in the blood the following morning, while findings were inconsistent with adrenaline and cortisol.[52,53] A study of approximately 5,000 individuals in Stockholm followed up for ten years found a Lden 5 dB(A) increase in aircraft noise was associated with a greater increase in waist circumference of 1.5 cm (95% confidence interval (CI): 1.13 to 1.89 cm)[54] but no associations were seen with body mass index (BMI).[55] The authors suggested that increased stress hormones might contribute to central obesity, measured by waist circumference and waist-hip ratio.

Aircraft noise and birth outcomes: There are only a small number of studies available. A recent systematic review[56] found that four of the five studies identified examining birth weight found associations between lower birth weight and higher aircraft noise. The largest study was conducted around a US military airfield in Japan,[57] examining 160,460 birth records from 1974 to 1993. The studies reviewed did not score highly on quality assessment and the authors of the systematic review concluded that more and better designed studies were needed.

Aircraft noise effects on psychological health: The evidence for aircraft noise exposure being linked to poorer wellbeing, lower quality of life, and psychological ill-health is not as strong or consistent as for other health outcomes, such as hypertension. A study of 2,300 residents near Frankfurt airport found that annoyance but not aircraft noise levels per se ($L_{A,eq,16hours}$, L_{night}, L_{den}) was associated with self-reported lower quality of life.[58] The HYpertension and Exposure to Noise near Airports (HYENA) study, found that a 10 dB increase in day-time ($L_{Aeq,16hours}$) or night-time (L_{night}) aircraft noise was associated with a 28% increase in anxiety medication use, but not with sleep medication or anti-depressant medication use.[59] A sub-study of the HYENA study found that salivary cortisol (a stress hormone that is higher in people with depression) was 34% higher for women exposed to aircraft noise above 60 dB $L_{Aeq,24hours}$, compared to women exposed to less than 50 dB $L_{Aeq,24hours}$,[60] but no associations were found for men. Studies in schools around London Heathrow airport found no effect of aircraft noise at school on children's psychological health or cortisol levels.[61-63] However, the West London Schools Study of 451 children aged 8-11 years found higher rates of hyperactivity symptoms for children attending schools exposed to aircraft noise exposure >63 dB $L_{Aeq,16hours}$

compared to children in schools exposed to levels below 57 dB $L_{Aeq,16hours}$.62 A similar effect was observed in the RANCH study.[63] These increases in hyperactivity symptoms, whilst statistically significant, were very small and most likely not of clinical relevance.

Conclusions: There is a good biological plausibility by which noise may affect health in terms of impacts on the autonomic system, annoyance and sleep disturbance. Studies are suggestive of impacts on cardiovascular health especially hypertension, but limited and inconclusive with respect to quantification of these, with a relatively small number of studies conducted to date. More studies are needed to better define exposure-response relationships, the relative importance of night versus daytime noise and the best noise metrics for health studies (e.g. number of aircraft noise events versus average noise level).

Civilian Supersonic Aircraft: A Future Source of Aviation Noise

Supersonic aircraft: All of the noise sources described thus far in this report pertain to noise in the vicinity of airports. In the future, however, it may be necessary to account for a new type of noise source that will be heard while the aircraft is in flight. Aircraft manufacturers are currently working on the design of supersonic civilian aircraft that produce a transient noise called a sonic boom. The sonic boom is pulled along with the aircraft analogous to the way a boat on a lake pulls its wake through the water. And just as the boat's wake impinges on the entire shoreline as it travels the lake, a supersonic aircraft's sonic boom impinges on the earth's surface for the entire supersonic journey. Because civilian supersonic aircraft are envisioned flying at altitudes upward of 15 km, the sonic boom noise might be heard within a corridor on the ground having a width of perhaps 100 km, centered on the aircraft's ground track. Fortunately, this noise will likely have a much lower level than traditional supersonic aircraft like Concorde due to the progress of technologists working to reduce the boom.

Noise regulations for sonic booms: Currently the world's noise regulations for supersonic aircraft exist from a time when the Concorde supersonic airliner was flying. The now-retired Concorde had a loud sonic boom, and the ICAO's Assembly Resolution A38-17 Appendix G protects individuals by reaffirming their position that "no unacceptable situation for the public is created by sonic boom from supersonic aircraft in commercial service." But there has been substantial progress during the last few years by industry, academia, and government laboratories developing supersonic aircraft technology, and by regulatory authorities that would certify such low-boom vehicles.[64-66] It is unclear how soon the new supersonic aircraft will be in widespread use, perhaps 20 to 30 years from now.

Conclusions

Noise is considered one, if not the most detrimental environmental effect of aviation. There is abundant evidence that aircraft noise exposure in the vicinity of airports is related to annoyance, and some evidence that the annoyance response has increased in recent years. There is sufficient evidence for a marked negative effect of aircraft noise exposure on children's cognitive skills, with some evidence that insulation of schools could mitigate this. There is also sufficient evidence that aircraft noise disturbs sleep and can impair sleep recuperation, but further research is needed to establish reliable noise exposure-response relationships and best mitigation strategies. Studies are suggestive of impacts of aircraft noise on health, but inconclusive with respect to quantification of exposure-response relationships, with a limited number of studies conducted to date. Mitigation of these various noise effects is necessary to protect the population living in the vicinity of airports and to address potential constraints to air traffic movements

Additional Information: Background, Including Noise Terms and Definitions

Noise definition: Noise is defined as "unwanted sound", and therefore has both an objective and a subjective component. Whether or not a sound is considered as noise depends both on its acoustical properties and its interference with intended activities. For example, attendees of a rock concert likely do not perceive the music as noise despite very high sound pressure levels (SPL). In contrast, residents living in the vicinity of the concert hall may perceive the music as noise despite much lower levels, as it may interfere with activities like reading a book or learning for school.

Aircraft noise characteristics: In contrast to, e.g., continuous road traffic noise from a busy road, aircraft noise is intermitted noise, i.e. consecutive aircraft noise events are usually separated by a noise-free period. During take-off, noise is predominantly generated by aircraft engines, while aerodynamic noise generated at flaps, gears, etc. may be more prominent than engine noise during landing.

Noise mitigation: The best noise mitigation measure is noise reduction at the source. Engineers were able to substantially reduce aircraft noise over the past decades (e.g., through high-bypass engines). Over the same period, air traffic volume increased substantially. Thus, people are exposed to a higher number of less noisy aircraft today. As it takes many years for new quieter aircraft designs to penetrate the market, different solutions are needed to reduce the number of people affected by relevant levels of aircraft noise. Potential measures include restricting how land is used near airports, changing how and where aircraft operate, limiting aircraft operations based on noise levels, limiting the hours that aircraft are allowed to operate, and providing sound insulation of homes and schools.

Noise monetization: Some States monetize the impacts of noise as a part of their policy making process. Within the U.S., the monetization of noise is based on the willingness of individuals to pay to avoid exposure to noise.[67] This method was used instead of observed differences in housing value as it is easier to gather income information than it is housing data. Within the U.K., Interdepartmental Group on Cost and Benefits (noise), IGCB(N), has developed guidance, which includes methods to quantify and monetize adverse health impacts, i.e. sleep disturbance, myocardial infarction, hypertension and dementia. During the ISG workshop, it was noted that even where methods exist to monetize these impacts, there is significant uncertainty in the results.

Noise monitoring: Many airports monitor noise levels on a regular basis. The equipment includes aircraft noise monitors, devices containing sound level meters, computer memory, and possibly communication equipment. The noise monitors are placed at strategic locations in the airport vicinity, often to assess the noise impact on selected neighborhoods or specific noise-sensitive locations such as hospitals or schools. By regular noise monitoring, an airport can ensure that the great majority of aircraft operations are within established noise limits.

Noise prediction: One of the additional tools used by airports and regulatory authorities are sound level contour maps, often just called noise maps. Using a combination of sound level measurements and appropriate sound mapping software, an airport can establish expected noise levels and determine, for example, locations where noise mitigation is needed. Looking down upon a map of the airport, the highest sound levels occur immediately next to the runways and along the primary aircraft takeoff and descent ground tracks. Moving away from these highest levels, decreased noise is found. Such noise maps can be very useful for assessing current and future noise exposure within several kilometers of airports.

Noise levels: This section will only provide the most basic information. For those who wish to dig deeper, there are a number of available references that explain the finer points.[68-70] Noise, or any type of sound, consists of fluctuations in pressure, p, measured in pascals (Pa), which is a force per unit area. Human hearing is extremely sensitive, and people hear very well over a wide range of pressures. Hence, to put this wide range into a more reasonable scale, logarithms are used.

The sound pressure level (SPL) is defined as

$$L_p = SPL = 20\log_{10}(p / p_{ref})$$

As you can see the logarithm to the base 10 is used, and the symbol utilized is L_p, indicating the level of the pressure. The reference pressure p_{ref} is a threshold of human hearing and equals 20 micropascals. A much larger pressure corresponding to a loud sound might correspond to 100 dB or higher. Very often to measure noise, an additional frequency weighting is used. Human hearing is not equally sensitive across all frequencies, and the most popular method to at least partially compensating for this is the A-weighting curve. A-weighting emphasizes the frequencies to which the human ear is most sensitive and attenuates the low frequency and very high frequency components of the sound. The A-weighted sound pressure level is denoted L_A. This metric is used commonly in assessing a wide variety of noise types, and is often described with the unit dB(A) or dBA.

Aviation noise metrics: Specific to aviation noise, a number of additional metrics are widely used. For single events, such as the passage of aircraft overhead, with its characteristic rising and falling of noise level over a minute or so, the A-weighted sound exposure level (ASEL) captures all of the energy of the event, and is given the symbol L_{AE}. The maximum level heard during the passage of the aircraft is denoted $L_{A\text{-}max}$. For multiple events, the average of those events is denoted L_{Aeq}, and sometimes the duration is specified (e.g., $L_{Aeq24hours}$ if the average is over an entire day). Aircraft noise can occur at any time, and sometimes the distinction is made between daytime and nighttime sound levels using the metrics L_{day} and L_{night}. To broadly account for the additional sensitivity to nighttime operations the day-night average level (DNL) is often used, denoted L_{DN}. It includes a 10 dBA penalty for any sounds occurring between the hours of 2200 and 0700. A 5 dBA penalty can be applied to operations in the evening hours, and this is called the day evening night sound level, denoted L_{den}. These metrics are all based on A-weighted noise levels. An alternative approach is to use the effective perceived noise level (EPNL), which has a more complicated definition found in the references.

References

1. Fields JM, De Jong RG, Gjestland T, et al. Standardized general-purpose noise reaction questions for community noise surveys: Research and a recommendation. Journal of Sound and Vibration 2001; **242**(4): 641-79.
2. Organization IS. ISO TS 15666: Acoustics - assessment of noise annoyance by means of social and socio-acoustic surveys. 2003.
3. Fields JM. Effect of personal and situational variables on noise annoyance in residential areas. JAcoustSocAm 1993; **93**(5): 2753-63.
4. Miedema HME, Vos H. Demographic and attitudinal factors that modify annoyance from transportation noise. JAcoustSocAm 1999; **105**(6): 3336-44.
5. Job RFS. Community response to noise - a review of factors influencing the relationship between noise exposure and reaction. JAcoustSocAm 1988; **83**(3): 991-1001.
6. Guski R. Personal and social variables as co-determinants of noise annoyance. Noise and Health 1999; **1**(3): 45-56.
7. Miedema HM, Oudshoorn CG. Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals. Environ Health Perspect 2001; **109**(4): 409-16.
8. Janssen SA, Vos H, van Kempen EEMM, Breugelmans ORP, Miedema HME. Trends in aircraft noise annoyance: The role of study and sample characteristics. JAcoustSocAm 2011; **129**(4): 1953-62.
9. Babisch W, Houthuijs D, Pershagen G, et al. Annoyance due to aircraft noise has increased over the years--results of the HYENA study. EnvironInt 2009; **35**(8): 1169-76.
10. Fidell S, Silvati L. Social survey of community response to a step change in aircraft noise exposure. JAcoustSocAm 2002; **111**(1 Pt. 1): 200-9.
11. Brink M, Wirth KE, Schierz C, Thomann G, Bauer G. Annoyance responses to stable and changing aircraft noise exposure. JAcoustSocAm 2008; **124**(5): 2930-41.
12. Fidell S, Mestre V, Schomer P, et al. A first-principles model for estimating the prevalence of annoyance with aircraft noise exposure. JAcoustSocAm 2011; **130**(2): 791-806.
13. Miedema HM, Vos H, de Jong RG. Community reaction to aircraft noise: time-of-day penalty and tradeoff between levels of overflights. JAcoustSocAm 2000; **107**(6): 3245-53.
14. Bates J, Taylor J, Flindell I, Humpheson D, Pownall C, Woolley A. Attitudes to noise from aviation sources in England (ANASE). Great Britan: MVA Consultancy, 2007.

15. Fields JM. The effect of numbers of noise events on people's reactions to noise: an analysis of existing survey data. JAcoustSocAm 1984; **75**(2): 447-67.
16. Schreckenberg D. Aircraft noise annoyance and residents' acceptance and use of sound proof windows and ventilation systems. Internoise; 2012; New York City, NY, USA; 2012.
17. Clark C. Aircraft noise effects on health: report prepared for the UK Airport Commission (Report number 150427). London: Queen Mary University of London, 2015.
18. Stansfeld SA, Berglund B, Clark C, et al. Aircraft and road traffic noise and children's cognition and health: a cross-national study. Lancet 2005; **365**(9475): 1942-9.
19. Clark C, Martin R, van Kempen E, et al. Exposure-effect relations between aircraft and road traffic noise exposure at school and reading comprehension - The RANCH project. Am J Epidemiol 2006; **163**(1): 27-37.
20. Clark C, Crombie R, Head J, van Kamp I, van Kempen E, Stansfeld SA. Does traffic-related air pollution explain associations of aircraft and road traffic noise exposure on children's health and cognition? A secondary analysis of the United Kingdom sample from the RANCH project. Am J Epidemiol 2012; **176**(4): 327-37.
21. Stansfeld SA, Hygge S, Clark C, Alfred T. Night time aircraft noise exposure and children's cognitive performance. Noise and Health 2010; **12**(49): 255-62.
22. Hygge S, Evans GW, Bullinger M. A prospective study of some effects of aircraft noise on cognitive performance in schoolchildren. Psychological Science 2002; **13**(5): 469-74.
23. Sharp B, Connor TL, McLaughlin D, Clark C, Stansfeld SA, Hervey J. Assessing aircraft noise conditions affecting student learning: Transportation Research Board of the National Academies, 2014.
24. Stansfeld S, Clark C. Health effects of noise exposure in children. Current Environmental Health Reports 2015.
25. Evans G, Lepore S. Non-auditory effects of noise on children: a critical review. Children's Environments 1993; **10**: 42-72.
26. WHO. Guidelines for Community Noise. Geneva: World Health Organization Europe, 2000.
27. Fritschi L, Brown AL, Kim R, Schwela DH, Kephalopoulos S, editors. Burden of disease from environmental noise. Bonn, Germany: World Health Organization (WHO); 2011.
28. Muzet A. Environmental noise, sleep and health. Sleep Medicine Reviews 2007; **11**(2): 135-42.
29. Dang-Vu TT, McKinney SM, Buxton OM, Solet JM, Ellenbogen JM. Spontaneous brain rhythms predict sleep stability in the face of noise. Current Biology 2010; **20**(15): R626-R7.
30. Basner M, Müller U, Griefahn B. Practical guidance for risk assessment of traffic noise effects on sleep. Appl Acoustics 2010; **71**(6): 518-22.
31. Basner M, Müller U, Elmenhorst E-M. Single and combined effects of air, road, and rail traffic noise on sleep and recuperation. Sleep 2011; **34**(1): 11-23.
32. Brink M, Basner M, Schierz C, et al. Determining physiological reaction probabilities to noise events during sleep. Somnologie 2009; **13**(4): 236-43.
33. Cassel W, Ploch T, Griefahn B, et al. Disturbed sleep in obstructive sleep apnea expressed in a single index of sleep disturbance (SDI). Somnologie 2008; **12**(2): 158-64.
34. Basner M. Nocturnal aircraft noise increases objectively assessed daytime sleepiness. Somnologie 2008; **12**(2): 110-7.
35. Elmenhorst EM, Elmenhorst D, Wenzel J, et al. Effects of nocturnal aircraft noise on cognitive performance in the following morning: dose-response relationships in laboratory and field. Int Arch Occup Environ Health 2010; **83**(7): 743-51.
36. Jarup L, Babisch W, Houthuijs D, et al. Hypertension and exposure to noise near airports: the HYENA study. EnvironHealth Perspect 2008; **116**(3): 329-33.
37. Basner M, Isermann U, Samel A. Aircraft noise effects on sleep: Application of the results of a large polysomnographic field study. JAcoustSocAm 2006; **119**(5): 2772-84.
38. Pearsons K, Barber D, Tabachnick BG, Fidell S. Predicting noise-induced sleep disturbance. JAcoustSocAm 1995; **97**(1): 331-8.
39. Marks A, Griefahn B, Basner M. Event-related awakenings caused by nocturnal transportation noise. Noise ContrEngJ 2008; **56** (1): 52-62.
40. Babisch W. The Noise/Stress Concept, Risk Assessment and Research Needs. Noise and Health 2002; **4**(16): 1-11.
41. Correia AW, Peters JL, Levy JI, Melly S, Dominici F. Residential exposure to aircraft noise and hospital admissions for cardiovascular diseases: multi-airport retrospective study. BMJ 2013; **347**: f5561.
42. Hansell AL, Blangiardo M, Fortunato L, et al. Aircraft noise and cardiovascular disease near Heathrow airport in London: small area study. BMJ 2013; **347**: f5432.
43. Floud S, Blangiardo M, Clark C, et al. Reported heart disease and stroke in relation to aircraft and road traffic noise in six European countries - the HYENA study. Epidemiology 2012; **23**(5S): E-039.
44. Huss A, Spoerri A, Egger M, Roosli M. Aircraft noise, air pollution, and mortality from myocardial infarction. Epidemiology 2010; **21**(6): 829-36.
45. Gan WQ, Davies HW, Koehoorn M, Brauer M. Association of long-term exposure to community noise and traffic-related air pollution with coronary heart disease mortality. Am J Epidemiol 2012; **175**(9): 898-906.
46. Sorensen M, Hvidberg M, Andersen ZJ, et al. Road traffic noise and stroke: a prospective cohort study. Eur Heart J 2011; **32**(6): 737-44.
47. Babisch W, Kamp I. Exposure-response relationship of the association between aircraft noise and the risk of hypertension. NoiseHealth 2009; **11**(44): 161-8.
48. Huang D, Song X, Cui Q, Tian J, Wang Q, Yang K. Is there an association between aircraft noise exposure and the incidence of hypertension? A meta-analysis of 16784 participants. NoiseHealth 2015; **17**(75): 93-7.
49. van Kempen E, Babisch W. The quantitative relationship between road traffic noise and hypertension: a meta-analysis. J Hypertens 2012; **30**(6): 1075-86.
50. van Kempen E, van Kamp I, Fischer P, et al. Noise exposure and children's blood pressure and heart rate: the RANCH project. Occup Environ Med 2006; **63**(9): 632-9.
51. Haralabidis AS, Dimakopoulou K, Vigna-Taglianti F, et al. Acute effects of night-time noise exposure on blood pressure in populations living near airports. Eur Heart J 2008; **29**(5): 658-64.
52. Schmidt FP, Basner M, Kroger G, et al. Effect of nighttime aircraft noise exposure on endothelial function and stress hormone release in healthy adults. Eur Heart J 2013; **34**(45): 3508-14a.
53. Schmidt F, Kolle K, Kreuder K, et al. Nighttime aircraft noise impairs endothelial function and increases blood pressure in patients with or at high risk for coronary artery disease. Clinical research in cardiology 2014.
54. Eriksson C, Hilding A, Pyko A, Bluhm G, Pershagen G, Ostenson CG. Long-term aircraft noise exposure and body mass index, waist circumference, and type 2 diabetes: a prospective study. Environ Health Perspect 2014; **122**(7): 687-94.
55. Pyko A, Eriksson C, Oftedal B, et al. Exposure to traffic noise and markers of obesity. Occup Environ Med 2015.
56. Ristovska G, Laszlo HE, Hansell AL. Reproductive outcomes associated with noise exposure - a systematic review of the literature. Int J Environ Res Public Health 2014; **11**(8): 7931-52.
57. Matsui T, Matsuno T, Ashimine K, Miyakita T, Hiramatsu K, Yamamoto T. [Association between the rates of low birth-weight and/or preterm infants and aircraft noise exposure]. Nihon Eiseigaku Zasshi 2003; **58**(3): 385-94.
58. Schreckenberg D, Meis M, Kahl C, Peschel C, Eikmann T. Aircraft noise and quality of life around Frankfurt Airport. Int J Environ Res Public Health 2010; **7**(9): 3382-405.
59. Floud S, Vigna-Taglianti F, Hansell A, et al. Medication use in relation to noise from aircraft and road traffic in six European countries: results of the HYENA study. Occup Environ Med 2011; **68**(7): 518-24.
60. Selander J, Bluhm G, Theorell T, et al. Saliva cortisol and exposure to aircraft noise in six European countries. Environ Health Perspect 2009; **117**(11): 1713-7.
61. Haines MM, Stansfeld SA, Job RF, Berglund B, Head J. Chronic aircraft noise exposure, stress responses, mental health and cognitive performance in school children Psychol Med 2001; **31**(2): 265-77.
62. Haines MM, Stansfeld SA, Brentnall, S., et al. The West London Schools Study: the effects of chronic aircraft noise exposure on child health. Psychol Med 2001; **31**(8): 1385-96.
63. Stansfeld SA, Clark C, Cameron RM, et al. Aircraft and road traffic noise exposure and children's mental health J Environ Psychol 2009; **29**(9): 203-7.
64. Fisher L, Liu L, Maurice L, Shepherd K. Supersonic aircraft: balancing fast, affordable, and green. Int J Aeroacoustics 2004; **3**(3): 181-97.
65. Liu S, Sparrow V, Makino Y. Establishing noise standards for civil supersonic aircraft: status report, 2013.
66. Maglieri D, Bobbitt P, Plotkin K, Shepherd K, Coen P, Richwine D. Sonic boom: six decades of research. Langley Research Center, 2014.
67. He Q, Wollersheim C, Locke M, Waitz I. Estimation of the global impacts of aviation-related noise using an income-based approach. Transport Policy 2014; **34**(0): 85-101.
68. Smith MJT. Aircraft Noise. Cambridge: Cambridge University Press; 1989.
69. Ruijgrok GJJ. Elements of aviation acoustics: Delft University Press; 2004.
70. Zaporozhets O, Tokarev V, Attenborough K. Aircraft noise: assessment, prediction, and control. Abingdon, UK: SPON Press; 2011.