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The role of noise annoyance for health-related effects of aircraft noise and recommendations for interventions

Sarah Benz[1], Julia Kuhlmann[1], Barbara Ohlenforst[2], Susanne Bartels [3], Sonja Jeram[4], Dirk Schreckenberg[1]

[1]ZEUS GmbH, Centre for Applied Psychology, Environmental and Social Research, Hagen, Germany
(benz@zeusgmbh.de, kuhlmann@zeusgmbh.de, schreckenberg@zeusgmbh.de)
[2] Royal NLR - Netherlands Aerospace Centre, Amsterdam, The Netherlands
(barbara.ohlenforst@nlr.nl)
[3] Sleep and Human Factors Research, Institute of Aerospace Medicine, German Aerospace Center (DLR), Cologne, Germany
(susanne.bartels@dlr.de)
[4]National Institute of Public Health, Environmental Health, Ljubljana, Slovenia
(sonja.jeram@nijz.si)

Abstract
Exposure to aircraft noise has been linked to health effects, e.g. cardiovascular disease, sleep outcomes, and noise annoyance. Recent studies suggest noise annoyance to mediate the effects of aircraft noise on other health outcomes. A similar mediating role of sleep disturbance is assumed for cardiovascular diseases as cross-sectional studies revealed that awakenings are accompanied by cardiovascular changes. Annoyance is regarded as a noise-induced stress response that is influenced by acoustic and non-acoustic factors (NAF) including coping capacities and perceived control. Also, for sleep disturbance, evidence exists for an influence of NAF. Whilst most interventions focus on reducing noise exposure, the potential to reduce noise-induced stress responses through tackling NAF can be considered as a promising new approach. We report implications for interventions at airports that directly address the reduction of citizens' responses related to non-acoustic factors.

Keywords: aircraft noise exposure, noise annoyance, sleep disturbance, health, interventions

1 Introduction

Aircraft noise exposure was found to be related to various adverse health effects [1], yet, a reduction in aircraft noise exposure does not necessarily result in lower noise-related effects, e.g. annoyance [2]. In 2018, the World Health Organization [1] published the Environmental Noise Guidelines for the European Region (ENG). Based on several systematic reviews covering scientific literature published between 2000 and 2014/2015, the ENG encompasses different recommendations of source-specific exposure levels to avoid harmful health effects of environmental noise and recommendations considering the health effects of noise interventions [1]. In the ENG, the WHO distinguishes critical and important health outcomes. The distinction between critical and important health outcomes is based on 'the seriousness and prevalence of the outcomes and the anticipated availability of evidence for an association with noise exposure" (p.10) [1]. The critical outcomes include cardiovascular diseases, effects on sleep, noise annoyance, cognitive impairment of children as well as hearing impairment and tinnitus, and the important outcomes encompass adverse birth outcomes, quality of life, well-being, and mental health, and metabolic outcomes.

For aircraft noise, within the framework of the European project ANIMA (Aviation Noise Impact Management through novel Approaches), we reviewed the scientific literature published since 2014 for new evidence of the impact of aircraft noise on the critical and important health outcomes as defined by the WHO [1], [3][4][5].
First, we report studies on the effects of those health outcomes that the WHO classifies as critical health outcomes in the ENG [1]: cardiovascular disease, sleep disturbance, and cognitive impairment. Results are briefly summarized. Second, we report findings that analyse the relationship between health effects and noise annoyance due to aircraft noise. Sleep disturbances were additionally identified as related to noise-induced health effects with less evidence [5]. Finally, we give recommendations to approach noise-related health issues by means of non-acoustic interventions.

2 Health effects of/related to aircraft noise

2.1 Cardiovascular diseases

Van Kempen et al. [6][7] conducted the systematic review that serves as the basis for the WHO recommendations on reducing the risk of cardiovascular diseases due to environmental noise. The review authors identified 600 references published between 2000 and 2015 that are related to the effects of transportation noise (rail, road, aircraft) and wind turbine noise on the cardiovascular and metabolic system. The investigated cardiovascular outcomes refer to hypertension (10 studies relating to aircraft noise), ischaemic heart diseases (IHD) and stroke (7 studies on aircraft noise for each outcome). No statistically significant increase in the risk of hypertension as well as stroke due to aircraft noise was identified after aggregating the results of the evaluated studies. A meta-analysis of the reviewed studies identified a relative risk of RR = 1.09 (1.04-1.15) per 10 dB increase in the day-evening-night level, $L_{\text{den,}}$ for the incidence of IHD based on results of 2 ecological studies with the evidence rated being of very low quality.
Recently published studies confirm evidence of nocturnal aircraft noise associated with a risk in hypertension, for the prevalence of hypertension reaching, e.g., an odds ratio of OR = 1.34 (1.00 – 1.97) per 10 dB increase in the nocturnal equivalent sound pressure level, L_{night}, [8] and for the incidence of hypertension reaching an OR = 2.63 (1.21 – 5.71) [9]. A large-scaled case-control study found no significant association between aircraft noise and hypertension [10]. However, in a subgroup the risk of hypertension with a subsequent diagnosis of hypertensive heart disease increased with OR = 1.139 per 10 dB increase in 24 hours equivalent continuous sound levels $L_{\text{Aeq,24h.}}$
In the ANIMA review, we included five publications on IHD, myocardial infarction, cardiac arrhythmia and heart failure. Besides equivalent continuous sound levels, such as $L_{\text{Aeq,24h}}$, L_{den} or L_{night}, additional noise metrics were used in recently published studies. For example, in the Swiss SiRENE study, the intermittency ratio, indicating the proportion to which single noise events emerge from the background, was found to be non-linearly associated with cardiovascular diseases, with strongest effect for mid-range intermittency [11]. In the French DEBATS study, the mortality rate ratio (MRR) was used to assess the increase in health risk due to aircraft noise [12]. For cardiovascular disease, the authors found an MRR increase of 18 % per 10 dB L_{den}. For coronary heart disease, MRR increased with 24 %, and for myocardial infarction with 28 % per 10 dB. The MRR risk increase was higher for men compared to women [12].
A study of the Swiss National Cohort around Zurich Airport considering data between 2000 and 2015 suggests that nocturnal aircraft noise can trigger acute cardiovascular mortality. The effect size of the association was found to be similar to that of previous studies for long-term aircraft noise exposure [13].
With regard to the impact of aircraft noise on stroke the evidence is still inconclusive. The WHO review [7] as well as the more recent RIVM review update [14], the review on aircraft noise and public health [15], and the ANIMA review identified no consistent significant increase of risk for stroke associated with increased aircraft noise exposure.

2.2 Sleep

The studies on noise-related sleep disturbances that were considered in the WHO review [1] indicate a significant positive association between L_{night} and the percentage of highly sleep disturbed people (*% HSD*). Further, the probability of additional aircraft noise-related awakenings was found to increase with an increase in the maximum sound pressure level, L_{ASmax}. The ANIMA literature review identified 24 additional relevant articles published between 2014 and 2021 [3][4][5]. The identified studies differ greatly with respect to measures used and the operationalization of the outcome. This makes a comparison more difficult.
Eight publications used physiological measurements; self-reports were used in 21 studies. Studies with a physiological measurement of sleep quality report an increase in wake time, time needed to fall asleep, motility and number of awakenings with increased nocturnal aircraft noise exposure. When looking at the probability of awakenings, the maximum sound pressure level seems to play the most important role.
One study examined the impact of a newly implemented night-flight ban at Frankfurt Airport and found the night-flight ban to benefit residents, for example, by decreasing number of awakenings per night and increase total sleep time [16]. However, the night-flight ban led to an increase in self-reported sleep disturbance and additional awakenings during morning hours as a lot of former night flights were re-scheduled from 5am onwards [2].
Most studies that used self-reports found aircraft noise exposure to influence the assessed sleep outcomes such as sleep disturbance and sleep quality. In line with the WHO review [17], the effect of aircraft noise exposure on sleep outcomes was higher in studies that specifically mentioned aircraft noise exposure as a potential source of the sleep disturbance. When questions asked about general sleep quality, sleep disturbance or insomnia criteria without mentioning aircraft noise, the effect of aircraft noise exposure on the outcome measure was not throughout significantly [5]. It seems as if the wording of the question can cause some bias as concluded before [17]. Mentioning aircraft noise as potential source of sleep disturbance may activate personal attitudes and expectations associated with the noise source. As there is ample evidence for the impact of non-acoustic factors including attitudes and expectations on annoyance ratings, it seems plausible that they (indirectly and unconsciously) impact on self-reports of sleep, too. In addition, study results indicate that aircraft noise exposure should not solely be assessed by average noise levels, but by, for instance, considering the maximum noise level and number of noise events per night as well.

2.3 Cognitive impairment/cognition

A few studies investigated the effects of aircraft noise on cognition, examining different outcome measures such as reading and oral comprehension, memory functions or children's educational achievements as an indicator for cognitive impairment. In the WHO review [18], the identified studies found moderate quality evidence showing aircraft noise exposure to negatively affect reading skills, oral comprehension, and poor long-term memory, among others.
An updated review within the ANIMA project identified one new study on cognitive effects in children: in the NORAH study around Frankfurt Airport the effects of aircraft noise on school children's cognition and quality of life were examined [19]. The study found effects of aircraft noise on reading ability confirming former results of the WHO review. A 10 dB increase in A-weighted equivalent continuous sound pressure levels (L_{Aeq}) was associated with a delay in reading abilities of about one month [19].

3 Noise annoyance and sleep disturbances as mediators for health effects

Babisch describes in his noise reaction scheme [20] the potential mechanism of how noise affects health outcomes. Sound exposure can evoke psychological and physiological reactions: cognitive, emotional and behavioural reactions (annoyance and disturbances) as well as physiological (stress) responses, e.g., of the endocrinological system. A prolonged activation of psychological and physiological stress mechanisms can cause critical biological changes. This in turn might contribute to the development of serious health effects.

3.1 Noise annoyance as a potential mediator of aircraft noise effects on health

There is a vast amount of studies investigating the effects of (aircraft) noise on health outcomes, but only a few studies consider the underlying mechanism.
One critical determinant assumed to play a key role in the process of developing health effects that are related to noise exposure can be found in noise annoyance. Noise annoyance is considered as a stress response [21] and manifests itself at the cognitive level (e.g. helplessness/perceived control), in emotional reactions (e.g. worry about potential harmful effects), and at the behavioural level (e.g. adapting behaviour when disturbed by noise) [22]. The evaluation of a sound situation is important for the perception of stress; additionally, physiological responses are directly linked to psychological stress responses; a mutual interaction is assumed. As the stress system is strongly associated with various health issues, noise annoyance is assumed to contribute to other health effects. In recent annoyance research, more attention was given to the relationship between noise annoyance and other health outcomes [23][24][25][26][27][28][29][30][31][32][33].
In several studies the relative risk for hypertension was found to be higher in people reporting annoyance than in people who are not annoyed [23][26][30]. In another study, no association was found between noise annoyance and increased blood pressure [29].
Sleep quality was associated with noise annoyance in a study by [24]: lower long-term aircraft noise annoyance was related to better sleep quality in a cross-sectional study.
Recent studies further studied the relationship between aircraft noise annoyance and mental health and well-being measures: In a study examining the impact of aircraft noise on children, [33] found an increase in aircraft noise annoyance to be accompanied by a decrease in children's self-reported physical well-being. Regarding research focusing on adults, [25] found participants reporting higher annoyance rates to be more likely to have higher risks for psychological distress in comparison to people reporting lower annoyance rates. Further, an increase of medication intake for anxiety disorders (anxiolytics) and also of antihypertensive medication was associated with noise annoyance [27]. Additionally, aircraft noise annoyance was shown to be related to healthy lifestyle behaviour: in a study on transportation noise, physical activity was negatively associated with transportation noise annoyance, in particular aircraft and road traffic noise annoyance, indicating that higher ratings of noise annoyance predicted future reduced physical activity[31].
Two longitudinal studies found indirect effects of aircraft noise exposure via noise annoyance on decrease in mental-health related quality of life [32] and on the number of reported depression cases [28].
These results emphasize a potential role of noise annoyance in the development of other health effects related to noise, although most studies have not used a longitudinal design.
In addition, the reversed causal pathway was analysed in two studies for the relationship between noise annoyance and mental-health related quality of life [32] and depression [28] with longitudinal data. Results indicated that poorer mental health also predicted higher noise annoyance levels a year later. This implies that vulnerable groups such as people with pre-existing illnesses or other health restrictions/issues might have limited resources to cope with the noise, which can contribute to higher annoyance rates. Corresponding to the stress mechanism, the exposure to noise can interfere with a person's ability to cope and prevent recreational processes. This further stresses that the appraisal of noise is important when considering reversed causality. General health status, vulnerability and additional strains can influence how a demanding situation or an environmental demand is perceived. In addition, living near an airport, i.e. being exposed to aircraft noise, can be considered as a situation that is characterised by uncertainty or unpredictability, which can trigger stress responses [34] and the ability to deal with this situation relates to people's coping capacities and perceived control.
These findings highlight the importance to focus on noise annoyance as a critical health outcome. However, the full pathway of the underlying mechanism in the development of noise-related health outcomes needs to be investigated in more detail.

3.2 Sleep disturbances as potential mediator for the effects of aircraft noise on health

For human beings, undisturbed sleep of sufficient length is vital. Healthy sleep provides the necessary daytime alertness, performance ability, and health [35].
Disturbed sleep due to noise together with noise annoyance are regarded as belonging to the possible key mediating variables in the causal chain from noise exposure to noise-induced cardiovascular and metabolic diseases [1]. The impact of noise on sleep and its further consequences can be classified as immediate reactions, short-term reactions and long-term consequences [36][37].
The immediate reactions to nocturnal noise refer to physiological stress processes such as the release of stress hormones, increase in blood pressure and heart rate. These noise-induced stress responses alter the balance in physiological processes referring to blood pressure, blood flow, blood lipids, carbohydrates (glucose) regulation, electrolytes, thrombosis/fibrinolysis, and vascular stiffness [37][38]. In consequence, these changes in stress responses, again, affect the sleeping behaviour in terms of changes in sleep stages from deeper to more lighter sleep stages, arousals, awakenings, reduced deep sleep time and increased total wake time and general loss of sleep [37]. The short-term consequences of a noise-related reduction in restoration during sleep is an increase in sleepiness, and reduction in well-being and cognitive performance during the next day [37].
In principle, the appearance of acute reactions to aircraft noise at night-time is not different from natural reactions, such as spontaneous awakenings. Nevertheless, if the number of these immediate reactions increases considerably, this is assumed to constitute health problems as it reduces the restorative power of sleep [37][17].
Long-term, chronic sleep disturbance is associated with vascular and systemic cerebral oxidative stress, and inflammation, leading, again, to cardiovascular and metabolic diseases. It is assumed that recurring noise-induced awakenings and the resulting sleep loss may account for the higher risks of negative health outcomes after a longer period of aircraft noise exposure [38].
The assumption that noise-induced sleep disturbance is part of the causal pathway from nocturnal exposure to increased risks for cardiovascular and metabolic diseases is often mentioned [e.g. [1]. However, evidence for the mediating effect of noise-induced sleep disturbance of the impact of nocturnal noise exposure on cardiovascular and metabolic diseases is scarce [38][39] or contradictory [40]. Very recently it was concluded that nocturnal aircraft noise exposure increases the risk of developing hypertension via a direct effect on blood pressure as well as via a mediated effect due to chronic sleep disturbance [39]. Additionally, aircraft noise exposure caused increased blood pressure, endothelial dysfunction, markers of vascular and systemic oxidative stress, and inflammation in mice during sleep but not during awake phases, pointing out the important role of disturbed sleep on long-term health effects [41]. However, as mediators such as noise annoyance seem to be relevant for long-term health effects as well [25][26], the relationship between the immediate and long-term effects of noise, such as recurrent appearance of disturbed sleep, chronic annoyance, and increase risks for cardiovascular, metabolic and mental diseases, is not completely clear, yet.

3.3 Interventions tackling non-acoustic factors

Reduction of noise exposure has not proved to fully reduce the predicted responses on noise [2]. An alternative way to tackle noise responses may be found in non-acoustic factors. Non-acoustic factors (NAF) have been shown to play a crucial role in the perception of noise and the development of noise annoyance [21]. Non-acoustic factors are physical, social, and internal characteristics of the surrounding areas or the affected person that influence the perception and processing of sounds [42]. Among others, NAF include attitudes, concerns, expectations or trust in authorities. There is evidence that such NAF not only lead to self-reports of noise effects. For example, an effect of NAF, at least with respect to attitudes, was also found for physiologically measured sleep quality [43]. Also, noise sensitivity is known to affect both self-reported noise responses as well as physiological reactions [e.g. [44]. Figure 1 illustrates roughly how short-term and long-term effects of aircraft noise, and non-acoustic factors are related.

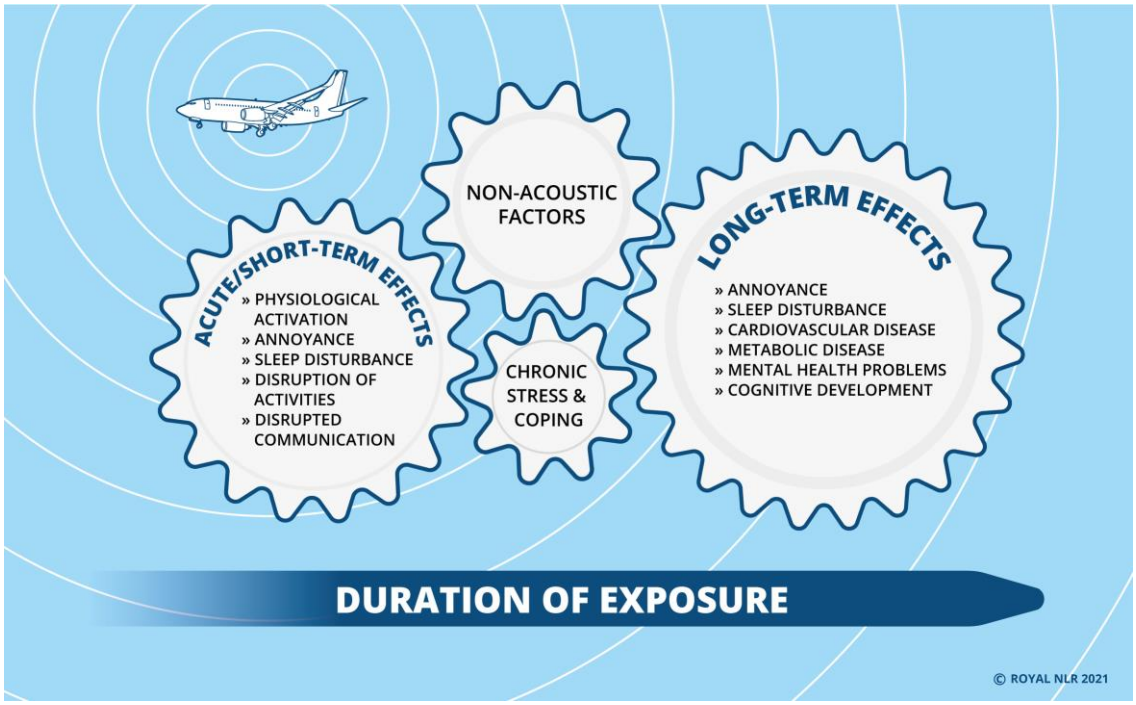

Figure 1 – Depiction of the link/relation between short-term and long-term health effects from aircraft noise.

4 Recommendations for interventions

The above-mentioned effects of noise annoyance on health highlight that noise exposure and noise annoyance have a considerable effect on people's wellbeing and health. Interventions that aim to reduce aircraft noise annoyance could help to reduce the experience of stress and other negative health outcomes. Therefore, interventions should not only focus on the reduction of the acoustic sound levels but in a broader sense take non-acoustic factors of annoyance and sleep disturbance into account as well.

The perception of being in control over the noise situation or having the opportunity to participate in aviation-related decisions could strengthen one's coping capacity and affect noise annoyance [45][46][47]. Perceived control can be enhanced by direct and immediate measures and by indirect measures [46]. Immediate measures correspond to direct actions that help controlling the noise exposure such as choosing a different location, recreational areas or respite locations or reducing the noise level by closing the windows. Community representatives and community engagement procedures that take the individual's concerns and opinions into account can indirectly create the perception of being in control. The perception of control can help to reduce the unpredictability of the noise exposure and the situation and in that way contribute to reduced noise annoyance. Transparent communication practises could be a way to support measures to reduce noise and noise responses [48].

One of the aspects that can help to create perceived control and reduce stress is the accessibility of recreational and respite areas. Being able to escape the noise exposure allows for restoring capacities that are diminished when dealing with ongoing noise annoyance and corresponding stress. Noise management should set more attention on interventions that target non-acoustic factors and people's perceived control in addition to efforts related to the reduction of aircraft noise exposure and sound levels. However, the larger uncertainty in the relation from NAF to annoyance (compared to the lower uncertainty between noise exposure and annoyance) display the need for studies that are designed to investigate the effects of interventions tackling noise annoyance through non-acoustic factors further.

The implementation of noise monitoring systems is a potential intervention that can provide feedback on the noise situation to residents and can enhance residents' perceived control. Another aspect of monitoring addresses the evaluation of interventions. It is important to monitor whether an intervention provides the expected efficacy. Some interventions might need to be adjusted over time as the surrounding circumstances might change and monitoring systems allows continuous evaluation.
There are many studies that focus on various outcomes of health effects caused by noise exposure and annoyance. However, the outcomes differ considerably and there is still a need to investigate effects of noise exposure on vulnerable population groups such as elderly people, children, chronically or mentally ill people or people with a lower socioeconomic status [49]. For instance, the amount of deep sleep loss in primary school children highly exposed to nocturnal aircraft noise resembles the amount of deep sleep loss in children with obstructive sleep apnoea syndrome. The small but recurrent disturbance of deep sleep in those children was concluded as a risk factor for the development of cardiovascular, metabolic and mental deficiencies in adult life [50]. Whether noise-induced deep sleep disturbance of similar magnitude has the same consequences needs to be subject of future research on the effect of transportation noise in the course of life. Furthermore, the vulnerability due to physiological and/or psychological health issues may limit resources to cope with noise, which can contribute to higher annoyance. Noise exposure and noise annoyance can impact educational level and socioeconomic status, physical and mental health parameters, phase in life, lifestyle factors and habits and therefore affect vulnerable population groups considerably [51][49].

5 Conclusions

Overall, there is evidence for a relationship between noise annoyance and sleep disturbance and other health outcomes. Recent noise impact studies further suggest that it is insufficient to solely rely on measures that focus on average noise level reduction, but rather consider a reduction in noise effects. Therefore, it is advised to combine measures to reduce noise responses with measures resulting in a reduced exposure. Results indicate that aiming at a reduction of annoyance and sleep disturbance responses could further decrease other health effects. Therefore, interventions should focus on the reduction of annoyance and sleep disturbance as well. The effects of interventions should be frequently evaluated.

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