

Aircraft noise effects on sleep: Substantiation of the DLR protection concept for airport Leipzig/Halle

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ABSTRACT

The Institute of Aerospace Medicine at the German Aerospace Center (DLR) investigated the influence of nocturnal aircraft noise on sleep in polysomnographical laboratory and field studies between 1999 and 2004. The results of the field study were used by the Regional Council of Leipzig (Germany) for the establishment of a noise protection plan in the official approval process for the expansion of Leipzig/Halle airport to an international freight hub. Of the results, special attention is given to the exposure-response relationship between the maximum sound pressure level of an aircraft noise event and the probability to wake up, which was used to establish noise protection zones directly related to the effects of noise on sleep. These protection zones differ qualitatively and quantitatively from zones that are solely based on acoustical criteria. The noise protection plan for Leipzig/Halle airport is presented and substantiated: (1) on average, there should be less than one additional awakening induced by aircraft noise, (2) awakenings recalled in the morning should be avoided as much as possible, and (3) aircraft noise should interfere as little as possible with the process of falling asleep again. Issues concerned with the representativeness of the study sample are discussed.

INTRODUCTION

Between 1999 and 2004, the DLR-Institute of Aerospace Medicine in Cologne, Germany, performed extensive laboratory and field studies on the effects of aircraft noise on sleep, mood and performance in the DLR/HGF-project "Quiet Air Traffic". The Regional Council of Leipzig (RCL) asked DLR to propose a concept for the protection of residents of airport Leipzig/Halle against the adverse effects of nocturnal aircraft noise on sleep based on the findings of the field studies. Leipzig/Halle airport was recently extended to an international freight hub with air traffic predominantly occurring during the night. The southern runway was turned and extended to a length of 3,600 m. Together with the northern runway, this independent parallel runway system allows for simultaneous takeoffs and landings. The traffic volume is predicted with 81,000 aircraft movements during the six busiest months in the year 2015. Of these, 45,600 will take place during the day between 6:00 und 22:00 and 35,400 will occur during the night between 22:00 und 6:00. Thus, a large part of aircraft movements will take place during night. This situation distinguishes Leipzig/Halle airport from most other airports worldwide.

DLR-INVESTIGATIONS AND RESULTS

Methods

Since the concepts of the noise protection plan for Leipzig/Halle airport are mainly based on the results of the DLR field study, study design and methods of the field study are briefly described. A detailed description is provided in the executive summary of the study (Basner et al. 2004). The field study was conducted in 2001 and 2002 with 64 residents of Cologne-Bonn airport, which is one of the German airports with the highest nighttime freight traffic densities. Subjects were investigated for 9 consecutive nights, starting on Mondays. They were selected in a multi-level process, and were between 19 and 61 years old (average: 38 years). 56 % of the participants were female. Subjects had to be free of intrinsic sleep disorders and had to have normal hearing thresholds according to age. The study protocol was approved by an ethics committee. Subjects were instructed according to the Helsinki declaration, participated voluntarily, and were free to discontinue their participation at any time without explanation.

Electroencephalogram (EEG), electrooculogram (EOG), electromyogram (EMG), electrocardiogram (ECG), respiratory movements, finger pulse amplitude, position in bed and actigraphy were sampled continuously during the night. With the EEG, EOG and EMG signals (also called polysomnography), sleep can be classified into different sleep stages (Rechtschaffen et al. 1968).

In the field study, sound pressure levels (SPL) and actual sounds were recorded inside the bedroom (at the sleeper's ear) and outside (2 m in front of the window) with class-1 sound level meters. All events (e.g. aircraft noise, road traffic noise, snoring, etc.) were identified by a human scorer. The start and the end of each event were marked. The simultaneous recording of acoustical and electrophysiological signals allowed for an event-related analysis with a maximum resolution of 125 ms.

Reactions to aircraft noise and spontaneous reactions (undisturbed by external stimuli) during sleep are non-specific. Hence, reactions observed during an aircraft noise event (ANE) cannot be differentiated from spontaneous reactions according to electrophysiological criteria. Furthermore, spontaneous reactions occur irregularly. Therefore, a reaction during an ANE occurs, it is important to examine how often this reaction would have taken place spontaneously anyway, i.e. without the influence of aircraft noise. The probability of spontaneous reactions can be estimated from periods without aircraft noise. In epidemiology the term attributable risk is often used in this context. Thus, the probability of a reaction additionally induced by aircraft noise according to Brink et al. (2006) is calculated as:

$$P_{\text{additional}} = P_{\text{ANE}} - P_{\text{spontaneous}} \quad (1)$$

Results

In total, 61 of 64 subjects contributed to the final analysis with 483 subject nights. The data of 3 subjects were discarded due to constant snoring (2 subjects) or an intrinsic sleep disorder (1 subject). The first night was not analyzed because of the so called first-night effect (Agnew Jr. et al. 1966). 10,658 ANEs met the inclusion criteria and contributed to the regression analyses.

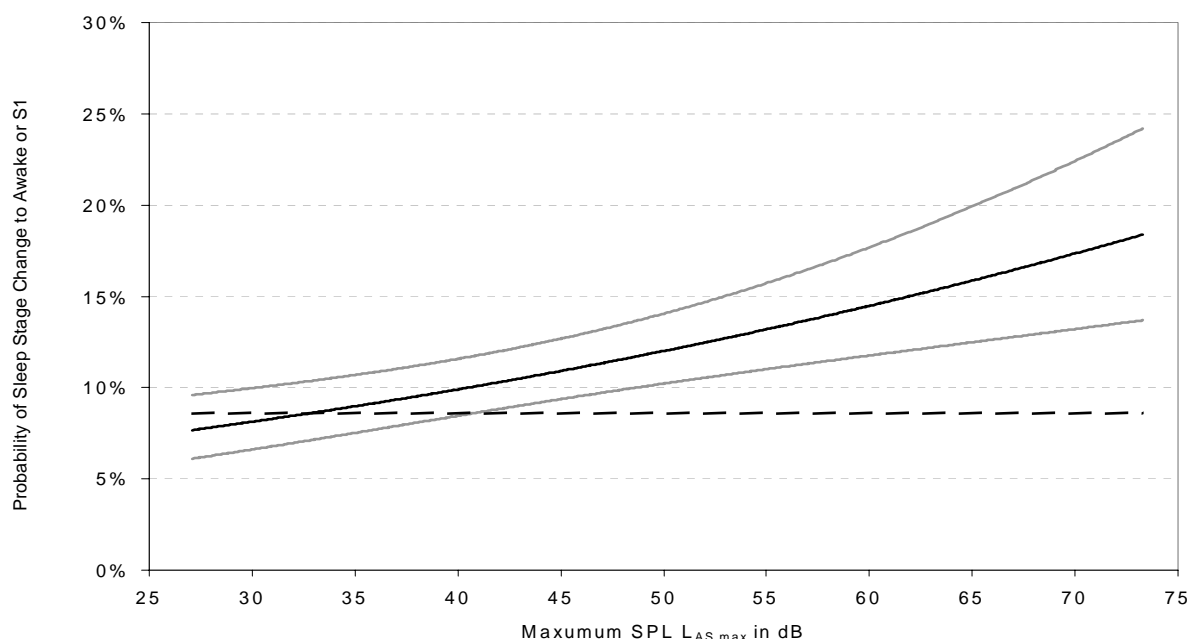


Figure 1: Probability of sleep stage change to Stage 1 or Awake depending on maximum SPL $L_{AS,max}$. Assumptions: Background noise level 27.1 dB, prior sleep stage Stage 2, elapsed sleep time 5 hours. Point estimates (black line), 95 % confidence limits (grey lines), and spontaneous reaction probabilities (dashed line) are shown.

Figure 1 illustrates the relationship between the maximum SPL of an ANE and the percentage awakened (black line). The background noise level was assumed constant with 27.1 dB (median of all measurements in the field study). For preventive reasons, the sleep stage prior to the ANE was assumed to be Stage 2 in all cases, i.e. the most sensitive sleep stage. Likewise, elapsed sleep time was set to the middle of the more sensitive second half of the night (about 5 hrs after sleep onset). The highest SPL measured in the field inside the bedroom was 73.2 dB. Spontaneous changes to Wake or Stage S1 occurred with a probability of 8.6 % (dashed line). A threshold value of about 33 dB was found, i.e. awakening probability increased only for ANEs with maximum SPL above 33 dB compared to spontaneous awakening probability (see Figure 1). This threshold was only 6 dB above the background noise level, which seems physiologically plausible: First noise induced awakenings should be observed when the auditory system is able to differentiate the ANE from the background noise. It must be emphasized that the awakening probability just above the threshold is very low: only 2 of 1,000 people exposed to an ANE with a maximum SPL of 34 dB will show a noise induced awakening. Due to the large number of subjects and ANEs, the precision of the point estimate is very high, i.e. the width of the 95 % confidence interval is very narrow (3.1 % at 39 dB and 10.5 % at 73.2 dB).

The probability of additional noise induced awakenings or changes to Stage 1 (according to equation 1) can be approximated with a second-degree polynomial between 32.7 dB and 73.2 dB. Awakening probability in percent is calculated as:

$$P_{AWR} = 1,894 \cdot 10^{-3} L_{AS,max}^2 + 4,008 \cdot 10^{-2} L_{AS,max} - 3,3243 \quad (2)$$

The probabilities calculated by the polynomial deviate less than 0.1 % from the original regression line within the specified interval.

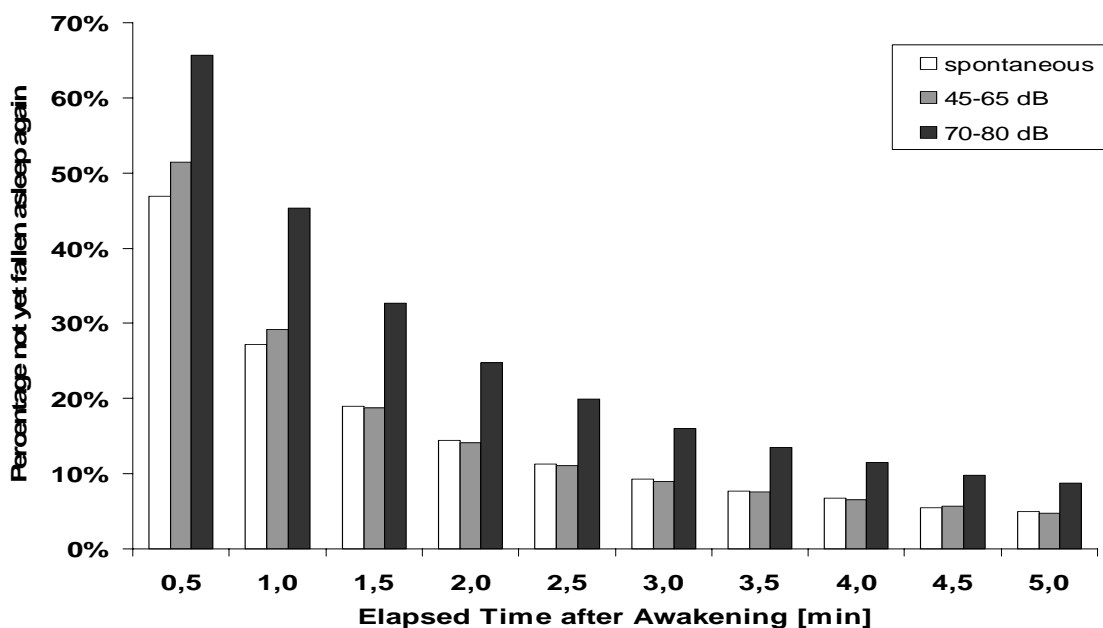


Figure 2: Duration of noise induced awakenings depending on maximum SPL and compared to spontaneous awakenings

Both number and duration of aircraft noise induced awakenings play an important role for the evaluation of the effects of aircraft noise on sleep, because the probability of a recalled awakening in the morning increases with awakening duration. Results of the DLR laboratory study showed that awakening duration increased with the maximum SPL of an ANE (see Figure 2). Awakenings induced by ANEs with maximum SPLs of 65 dB or lower were relatively short. After 1.5 min, descriptively no difference in the percentage of subjects having fallen asleep again compared to spontaneous awakenings was observed. In contrast to that, awakenings induced by ANEs with maximum SPLs of 70 dB or higher were markedly longer than spontaneous awakenings.

DLR-CONCEPT FOR NIGHTTIME PROTECTION

Objectives of the concept

Adequate protection of people affected by nocturnal aircraft noise has to be the main objective of a protection concept in order to prevent negative health consequences. Changes in sleep structure that may lead to a non-restorative sleep are the primary effects of nocturnal aircraft noise. Sleepiness and impaired mental capacities are two of the possible immediate consequences (Basner 2008). Furthermore, annoyance may be induced by consciously perceived noise events during the night. It is also being discussed whether repeatedly (over years) occurring noise induced sleep disturbances may lead to other health impairments, such as an increased risk for high blood pressure or myocardial infarction (Babisch 2000; Babisch et al. 2005; Jarup et al. 2008; Morrell et al. 1997). If established, these noise impacts on health would be of major societal importance. However, in practice it is very difficult to substantiate a causal link between noise and long term health effects, as many different and well proven risk factors lead to the same diseases and induction periods are usually very long. In order to overcome this dilemma, the DLR-concept is based on two assumptions: (i) Because of biological plausibility, it is hypothesized that a causal link between noise induced sleep disturbances and long term health effects exists. Vice versa, long term health effects can be prevented with a high probability if noise in-

duced sleep disturbances are minimized. (ii) It is assumed that humans – like any organism – represent an adaptive system, which is able to compensate for certain strains without negative effects for the organism. Hence, it is not necessary to eliminate strains completely.

Description of the concept

The DLR-concept is founded on three objectives reflecting three highly correlated dimensions of sleep:

- (i) On average, there should be less than one additional awakening induced by aircraft noise. Here, awakenings are defined as an electrophysiological phenomenon classified according to the rules of Rechtschaffen et al. (1968).
- (ii) Awakenings recalled in the morning should be prevented as much as possible.
- (iii) There should be no relevant impairment of the process of falling asleep again.

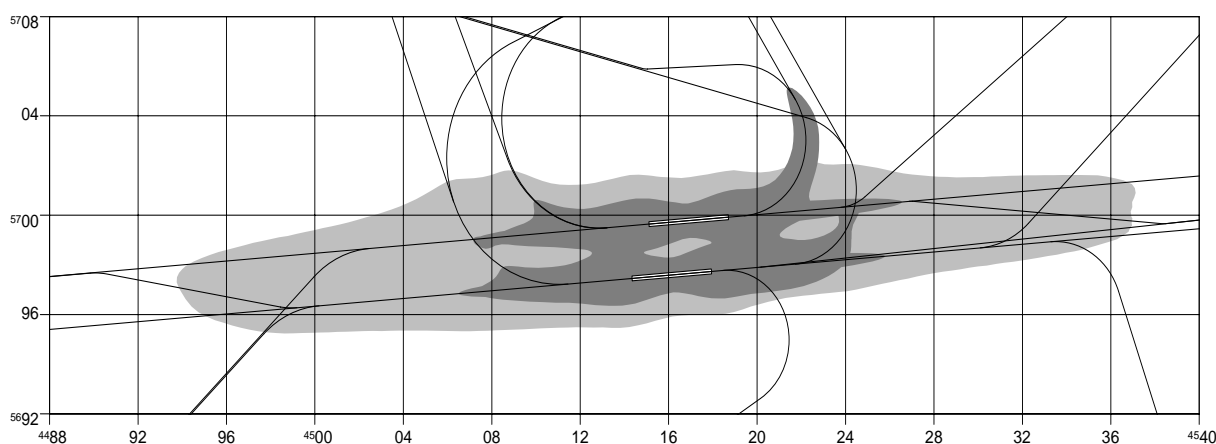


Figure 3: Noise protection zone for airport Leipzig/Halle (traffic prognosis for 2015), consisting of the combination of two areas: (1) area outside of which less than one additional awakening induced by aircraft noise is expected on average (light grey, expected distribution of directions of flight movements); (2) area outside of which maximum SPLs of 80 dB or higher (measured outside) occur less than once (dark grey, 100:100 distribution of directions of flight movements)

Figure 3 illustrates the proposed noise protection zone for Leipzig/Halle airport for the night (22:00 until 06:00), based on a traffic prognosis for 2015. Two contours are combined: Outside of the light grey area on average less than one additional awakening induced by aircraft noise is expected. This contour is based on the expected, average distribution of flight movements on the two operation directions. Outside of the dark grey area, maximum SPLs of 80 dB or higher (measured outside) occur less than once. This contour is the envelope of two contours estimated for a 100 % distribution of flight movements in both operating directions. This leads to an overestimation of effects, which was intended as awakenings recalled in the morning are regarded especially serious sleep disturbances.

An individual wakes up or does not. Thus, criterion (i) must be interpreted as a statistical value which has a distribution over nights and persons. If an individual is awakened by aircraft noise more than once in one night, there must be other nights with no additional awakening for compensation. Summarizing e.g. over a year, the criterion allows not more than 364 additional awakenings. This number has to be kept in mind compared to about 24 spontaneous awakenings to be expected per night on average and therefore about 8,760 spontaneous awakenings per year (Basner et al. 2004).

Criterion (ii) considers the risk of recalled awakenings in the morning. Recalled awakenings are correlated with subjective sleep quality and quantity ratings: The higher the number of recalled awakenings, the worse the estimation of sleep quality and quantity. ANEs during a sleep period influence the assessment of annoyance only when they are perceived consciously, and longer awakenings are a prerequisite for regaining consciousness (Health Council of the Netherlands 2004). Recalled awakenings not only fragment sleep. They have psychological disadvantages as well and therefore form a major sleep disturbance. Psychosomatic disorders cannot be excluded if recalled awakenings are induced over longer time periods. Therefore, from a medical point of view, recalled awakenings induced by aircraft noise should be prevented as much as possible. The 1st criterion limits the number of noise induced awakenings irrespective of the duration of the awakenings, and, thus, limits the number of recalled awakenings as well. Analyses of the laboratory study showed that the duration of noise induced awakenings increases with the maximum SPL of ANEs. Relevant differences compared to spontaneous awakenings were observed for maximum SPLs of more than 65 dB (see Figure 2). For this reason, maximum SPLs of more than 65 dB should be avoided in the bedroom. For a tilted window with an assumed difference in SPLs of 15 dB between inside and outside, the 1 x 80 dB_{outside}-contour of Figure 3 (dark grey) assures that outside this area maximum SPLs of 65 dB are exceeded less than once per night inside the bedroom on average. As recalled awakenings should be avoided as much as possible, this contour is based on a 100 % flight movements in one direction estimation, i.e. the worst case.

The problem of falling asleep again (criterion (iii)) has practically not been considered in the literature of noise effects on sleep so far, disregarding the fact that about 7 % of the sleep period are spent awake (Basner & Samel 2005). ANEs can prevent the sleeper from falling asleep again in these situations, and therefore have a negative impact on sleep structure (Basner et al. 2004). The traffic prognosis for Leipzig/Halle airport in 2015 forecasts two very busy periods during the night caused by freight traffic. Between 0:00 and 1:30 up to 60 approaches per hour and between 4:00 and 5:30 up to 50 starts per hour are expected. The short time period between two noise events in these peak hours leads to an increased risk of preventing the affected population from falling asleep again. If a subject already regained consciousness, annoyance reactions may result from consciously perceived noise events. Indeed, many airport residents complain about ANEs in early morning hours. A complex model was built, based on extensive analyses of the data of the field study to assess the impact of aircraft noise on falling asleep again, depending on maximum SPL $L_{AS,max}$ of the ANE, elapsed sleep time, the current state (awake/sleep) and the elapsed time spent in the same sleep stage (Basner & Siebert 2006). The results indicated that maximum SPLs of ANEs in the second half of the night should receive a malus of 1.4 dB, i.e. they should be artificially elevated by 1.4 dB, in order to assure an undisturbed process of falling asleep again similarly in all regions around Leipzig/Halle airport.

REPRESENTATIVENESS ISSUES

In the DLR field study, 64 subjects were studied for 576 subject nights, resulting in the largest polysomnographical study with identical methodological approach so far. Nevertheless, the study does not claim representativeness for the whole population. It is impossible to be representative for a whole population in a study with huge methodological expenses for a single subject like the DLR study. Additionally, some inclusion criteria had to be met in order to be eligible for study participation, leading to

a higher internal validity of the results. This is a prerequisite for external validation, but also restricts it to some extent (Basner et al. 2004).

Therefore, the results of the field study were not transferred 1:1 to the population living in the vicinity of Leipzig/Halle airport. Instead, several preventive measures were taken in order to protect those parts of the population that were not represented in the DLR field study and/or that are more sensitive to aircraft noise than the average sleeper. Some of these measures shall be briefly summarized:

- Subjects assessing themselves as sensitive to and annoyed by aircraft noise were included preferably into the study. 75 % of study subjects assessed themselves as moderately, strongly or very strongly annoyed, which compares well to a recent representative survey at Frankfurt airport (Schreckenberk & Meis 2006).
- Not only awakenings, but also sleep stage changes to Stage 1 were regarded as relevant noise induced sleep disturbances, increasing the probability of reactions to aircraft noise.
- For the calculation of the dose-response curve based on the regression results it was assumed that the sleeper spent the whole night in the most sensitive sleep stage S2 and in the middle of the more sensitive second half of the night. In reality, an average night contains only about 50 % of sleep Stage 2. Hence, the dose-response curve is shifted to higher probabilities compared to calculations where the actual sleep stage distribution is used. Because of this measure alone the noise protection zone increases from 156 km² by 28 % to 199 km².
- Subjects with illnesses lowering noise sensitivity (e.g. Hypakusis, Hypersomnolence) were excluded from study participation.
- The calculations for the noise protection zone were based on the six busiest months of the year according to air traffic.
- Sound insulation was increased by 3 dB for sensitive institutions (e.g. hospitals) and individuals with relevant diseases accompanied by higher noise sensitivity.

The proposal of allowing only one additional awakening induced by aircraft noise makes sense in terms of preventive medicine. It has to be taken into account that on average 24 spontaneous awakenings can be observed in an otherwise undisturbed night anyway.

SUMMARY AND CONCLUSIONS

The DLR-Institute of Aerospace Medicine investigated the influence of aircraft noise on sleep, mood and performance in an extensive polysomnographical field study between 1999 and 2004 as part of the DLR/HGF-project "Quiet Air Traffic". The dose-response relationship developed in this study was used to establish a concept for the protection of subjects against the adverse effects of nocturnal aircraft noise on sleep. The Regional Council of Leipzig decided to use the results of the DLR field study for developing a new noise protection concept at Leipzig/Halle airport. This concept culminates in the three propositions and reflects three correlated dimensions of sleep: There should be on average less than one additional awakening induced by aircraft noise, noise induced awakenings recalled in the morning should be prevented as much as possible, and no relevant impairments of the process of falling asleep again should occur. These three provisions have been proposed in order to consider the special conditions under which Leipzig/Halle airport will operate: (i) construction of a second independent runway, (ii) settlement of a night cargo hub for a big service provider, (iii) heavy air traffic during night including peak hours with up to 60 movements per hour and (iv) practically no nocturnal air traffic in the present. These circum-

stances necessitate a special concept for the protection of the affected population against the adverse effects of nocturnal aircraft noise on sleep.

With the decision to implement the results of the DLR field study, fresh ground was broken, as noise protection zones solely depended on acoustical criteria so far. The noise protection zone for nocturnal air traffic proposed by DLR exceeds the one of a current law amendment under discussion, which should come in force in 2011, by 60 km².

Shortly after the publication of the official documents of the approval process for the extension of Leipzig/Halle airport in November 2004, the integrator DHL decided to move its European freight hub from Brussels to Leipzig/Halle. Despite of the very conservative approach taken in constructing the noise protection zones, some residents living in the vicinity of Leipzig/Halle airport are still not satisfied with the concept: They sued in order to prevent the start of constructions at the airport. The Federal Administrative Court rebutted this sue in May 2005, and the construction measures started in August 2005. The final decision by the Federal Administrative Court from 09 November 2006 supports the DLR protection concept in every aspect. Recently, Leipzig/Halle freight hub commenced its work.

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