AIRCRAFT NOISE EFFECTS ON SLEEP: DLR RESEARCH AND APPLICATION TO A GERMAN AIRPORT

[1]A Samel†, [1]M Basner, [2]U Isermann, [1]H Maaß, [1]J Quehl
[1]German Aerospace Center (DLR), Institute of Aerospace Medicine, D-51170 Cologne
[2]German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology, Bunsenstr. 10, 37073, Goettingen
Germany

OVERVIEW

DLR studied human reactions to nocturnal aircraft noise in laboratory and field experiments for developing sound criteria for the protection of residents living near airports. The results of the field studies served to develop a protection concept against aircraft noise during night. This concept was used by the Regional Council of Leipzig for establishing the noise protection plan in the official approval process of the expansion of airport Leipzig/Halle.
Of the results, special attention is given to the dose-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, less than one additional awakening should be induced by aircraft noise, (2) awakenings recalled in the morning should be avoided, (3) aircraft noise should interfere with the process of falling asleep again as little as possible.
This protection plan was accepted by the Federal Administrative Court (Bundesverwaltungsgericht), to allow rapid cargo air transportation during night at the airport Leipzig/Halle.

1. INTRODUCTION

Sleep is vital for the recovery of physical and mental capacities. Aircraft noise (as all environmental noise) is able to interfere with the sleep process. In order to develop scientifically sound criteria for the restriction of nocturnal air traffic, the DLR-Institute of Aerospace Medicine investigated the influence of nocturnal aircraft noise on sleep, mood and behaviour in four large laboratory and two extensive field studies between 1999 and 2004.
Although much is known about the annoying effects of aircraft noise [8], the impact of aircraft noise on human physiology and performance is much less clear. Particularly, investigations into human sleep by classic polysomnographical methods are rare and were performed with small subject samples and led to divergent results. Therefore, assessing sleep by means of polysomnographic measures, i.e. electroencephalogram (EEG), electrooculogram (EOG), electromyogram (EMG) and electrocardiogram (ECG), was central for the project. In addition, several other physiological and psychological measures were taken, such as assessment of stress hormones, performance, annoyance and well-being, since former investigations on some of these functions have been shown ambiguous results. The results concerning the hormone production due to noise stress are contradictory [1,6], whereas results regarding annoyance by environmental noise led to the development of dose-response relations, distinguishing between the main traffic modes, air, rail and road traffic [8].
The development of dose-response relationships between acoustical parameters and objective and subjective sleep parameters play an important role in defining limits for the load of nocturnal air traffic. Thus, a major goal of the DLR-investigations was to establish dose-response relationships for sleep disturbances by aircraft noise and for various other body functions.

2. METHODS

In the laboratory, 128 subjects volunteered, in the field (i.e. at the subjects´ home), 64 subjects participated in the studies. In total 2240 nights were examined. In general, all physiological and psychological methods were similarly applied under both experimental conditions.

2.1. Laboratory studies

128 volunteers free of intrinsic sleep disorders and aged 18-65 (mean age: 38) were examined for 13 consecutive nights in the soundproof isolation facility (Fig 1). 8 separate sleep cabins allowed the simultaneous observation of 8 volunteers. 16 subjects served as a control group and did not receive aircraft noise. For the other 112 subjects, aircraft noise events (ANEs) were played back during 9 nights (nights 1 and 2 as well as nights 12 and 13 served as adaptation, baseline and recovery nights respectively) between 4 and 128 times per night with maximum sound pressure levels $L_{AS,max}$ between 45 and 80 dB(A). This corresponded to an equivalent sound pressure level $L_{AS,eq(3)}$ between 30 and 53 dB(A) within the interval of 8 hours of sleep. The combinations of frequency and $L_{AS,max}$ over the 9 noise nights were drawn in a random fashion. In each study night, always the same noise event with its characteristic $L_{AS,max}$ was presented to all 8 volunteers. In the bedroom, the microphone was positioned near the pillow. The windows were closed or tilted. In order to guarantee realistic playback of ANEs, each sleep cabin was acoustically calibrated. A trigger signal was recorded simultaneously with the electrophysiological data allowing for an event correlated analysis with a resolution of 125 ms. In total, more than 33,000 ANEs were played back in the laboratory studies.

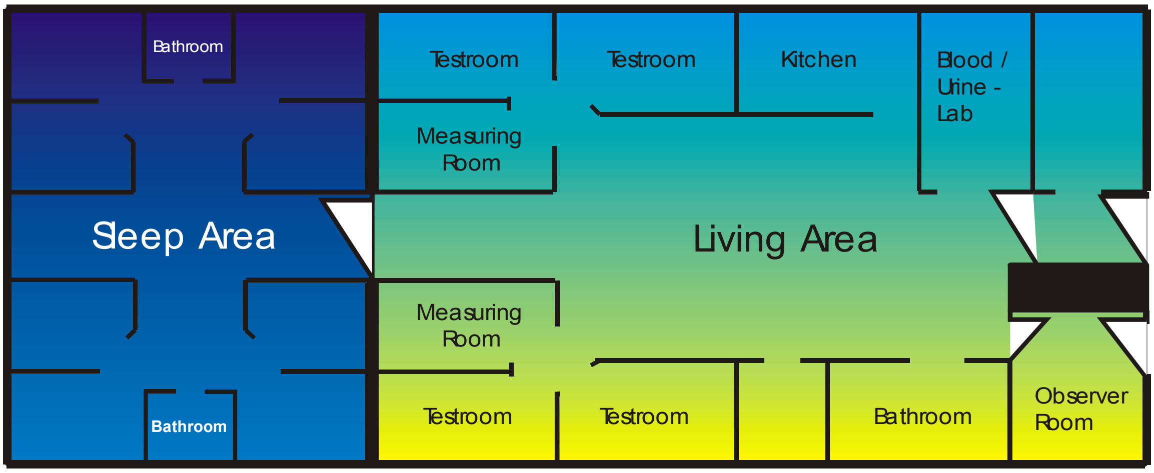

FIG 1. Isolation facility of the DLR-Institute of Aerospace Medicine. The area of the facility is 300 m^2. Eight subjects can be investigated at the same time

Occurrences of sleep disturbances (primary effects of aircraft noise) were assessed by electrophysiological parameters containing the EEG, EOG, EMG and EKG, respiration, finger pulse amplitude and position in bed. These signals have been recorded together simultaneously with the acoustic data in order to calculate event-correlated reactions. According to Rechtschaffen & Kales [10], each night was divided into 30-second segments each segment of sleep can be classified into the wake state and five distinct sleep stages: stages 1-4 and REM sleep. Stage 1 and stage 2 sleep are called light sleep, whereas stage 3 and stage 4 are known as deep or slow wave sleep (SWS). REM-sleep and especially deep sleep seem to be very important for the process of memory consolidation, whereas stage 1 sleep seems to contribute only little if all to the recuperative value of sleep.
As possible further effects of aircraft noise on sleep, the concentration of electrolytes (potassium, sodium, magnesium, and calcium) and stress hormones (cortisol, adrenalin and noradrenalin) were determined from all night urine samples. Aliquots were if required acidified, immediately deep frozen for their respective determination of the concentrations of these hormones. From concentrations and collection periods mean flux rates (absolute and relative) for the appropriate stress hormones resulted. We compared flux rates and respectively, equivalent sound pressure levels, maximum sound pressure levels and frequencies of aircraft noise events.
In the morning each subject filled in questionnaires on individual's night sleep and subjective noise sensations as well as on fatigue, well-being, mood and annoyance [11]. Annoyance due to nocturnal aircraft noise was evaluated using a 5-point rating scale ranging from "1 = not annoyed" to "5 = very annoyed".
Moderators like age, sex were considered in the statistical analyses of the data as well as the fact that single subjects were investigated repeatedly over several nights, i.e. non-independency of data. Therefore, data were analyzed with mixed models (PROC MIXED in SAS, version 8.2 and EGRET).

In the field studies, 64 volunteers aged 19-61 (mean age: 38) were investigated in the vicinity of Cologne Airport, which is one of Germany's airports with the highest number of nocturnal starts and landings. The ANEs occurring during the night were simultaneously recorded outside and inside the bedroom. In total, more than 15,000 ANEs were recorded. The same physiological and psychological variables as in the laboratory were continuously sampled in the field. Again, the simultaneous recording of electrophysiological data and a trigger signal allowed for an event correlated analysis with a resolution of 125 ms.
Furthermore, the data were analysed using the same statistical methods as in the laboratory.

3. RESULTS

In this paper, only a part of the results can be presented. Therefore, mainly dose-response curves of different functions are shown. An extended executive summary report of the project [2] as well as some additional detailed research reports were published [7,11].

3.1. Dose-response relations for aircraft noise induced awakenings

To establish relations between maximum sound pressure levels $L_{AS,max}$ and the number of awakenings caused by ANEs, spontaneous awakenings had to be considered. Spontaneous awakenings are part of normal sleep and occur irregularly; thus, they may also occur during an ANE. In the laboratory study it was found [2], that on average 24 spontaneous awakenings occurred during an average sleep period of 444.5 min. The probability $P_{induced}$ of a reaction induced by aircraft noise was therefore calculated as

$$P_{induced} = P_{ANE} - P_{spontaneous}$$

Under consideration of spontaneous awakenings, Fig 2

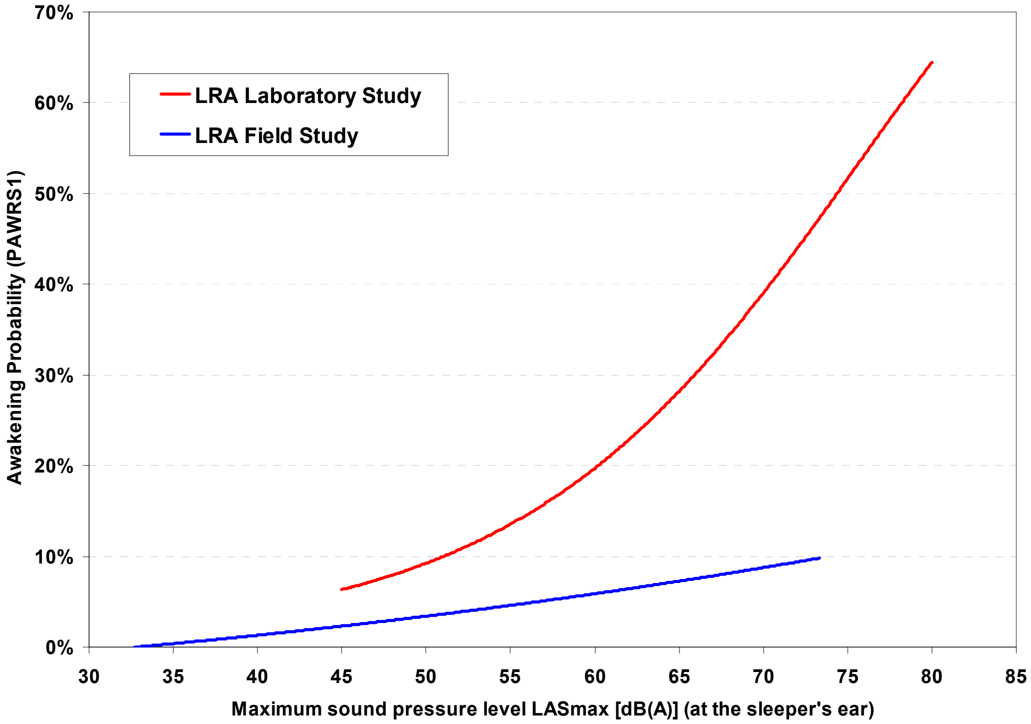

FIG 2. Random effects logistic regression. Comparison of the results of laboratory and field studies. Probability of awakenings attributable to aircraft noise events are depicted (noise induced awakenings and changes to sleep stage 1).

shows the dose-response relationships found in the laboratory and in the field studies. Only probabilities of noise induced awakenings are shown, i.e. the probabilities of spontaneous awakenings have already been subtracted. The curves are shown only over the range of observed maximum sound pressure levels (SPLs) at the sleeper's ear, i.e. between 45 and 80 dB(A) in the laboratory and up to 73.2 dB(A) in the field. The precision of the laboratory curve (95% confidence interval) was between 3.2% at 49.5 dB(A) and 7.5 dB(A) at 80 dB(A). The precision of the field curve varied between 3.1% at 39 dB(A) and 10.5% at 73.2 dB(A). The curves show the probability of an awakening from the most sensitive sleep stage 2 and were also calculated under the assumption that sleep time elapsed to the more sensitive second part of the night.

The differences between laboratory and field studies were obvious. They were observed over the whole range of the maximum SPL. The differences in awakening probability simultaneously grew with increasing SPL. The relatively low probability of noise induced awakenings in the field compared to the laboratory was reported by Pearsons [9] as a result of a meta-analysis of several studies conducted with traffic noise and sleep. One reason for the low awakening probabilities observed in the field studies is the fact that subjects were investigated in their familiar environment of their home and their own bed. This observation is supported by other authors: Hume and Whitehead [5] conducted a study where ANEs were presented to subjects by loudspeakers in their own homes, leading to awakening probabilities that were lower compared to those usually observed in the laboratory. These awakening probabilities, however, were still higher than those reported by Pearsons [9], which were assessed from field studies with real life noise events.

Therefore, not only the familiar housing environment, but also habituation to a specific noise environment at home may play an important role. These findings and conclusions are supported by an analysis of a sub-sample of 20 subjects who participated in both, the laboratory and the field studies. At home, their awakening probability resembled the field curve, while in the laboratory, the probability resembled the laboratory curve (Fig 2).

Besides the establishment of a dose-response relationship between maximum SPL and awakenings, the finding of a threshold for aircraft induced awakening under field conditions is important, whereas in the laboratory no threshold was found in the $L_{AS,max}$ interval between 45 and 80 dB(A). This threshold was 33 dB(A) and lay only 6 dB(A) above the measured background level of 27 dB(A). This result seems physiologically plausible, since first noise-induced awakenings should be observed once the human auditory system is able to differentiate ANEs from the background level. It should be emphasized that the awakening probability just above the threshold is very low (e.g. 0.2% of people exposed to an ANE of a maximum SPL of 34 dB(A) are expected to show a noise-induced awakening).

3.2. Dose-response relations for annoyance induced by aircraft noise during sleep

In these studies, subjects were specifically asked in the morning on their actual fatigue, mood, subjective sleep quality and quantity, and annoyance after each night with or without noise exposure. Thus, these parameters corresponded directly to the experienced noise conditions of the night before.

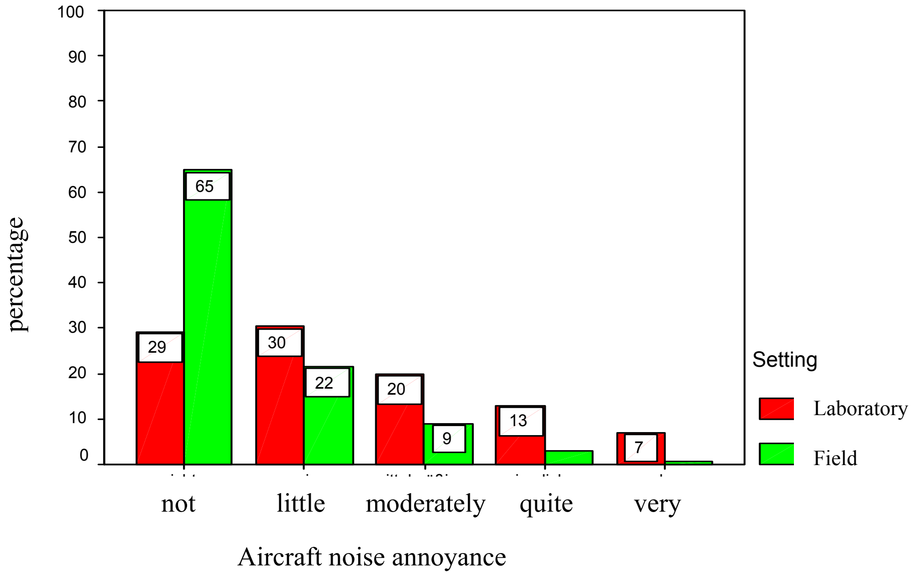

FIG 3. Distribution of annoyance responses (Question: “How strong were you annoyed by aircraft noise during the last night?”) in the laboratory (N=112) and the field (N=64). Categories are “not”, “little”,”moderate”, “quite” and “very”.

No significant dose-response relationships have been found with respect to all investigated parameters except annoyance. This was only possible, when combining the three (of five) upper categories of annoyance (i.e. combining the responses “moderate”, “quite” and “very” annoyed). This is unlike the common consideration on evaluation on the upper 25-30% of the rating scale constituting the group of highly annoyed persons according to Schultz [12]. The procedure used in these studies was reasonable because merely 20% of all laboratory annoyance ratings and only 4% of all field assessments contributed to on the scale categories “quite” and “very” (Fig 3). However, the medium score “moderate” was included into the analysis, since otherwise subjects moderately bothered by aircraft noise during sleep had been ignored.
The dose-effect curves of annoyance are shown in Fig 4, separately for the laboratory and the field. Personal moderators (e.g. age, gender, noise sensitivity) and those which were related to aircraft noise specific aspects (e.g. ratings concerning health effects, attitude towards air traffic), were considered and significance was tested. The curves indicate that annoyance increases with elevated noise load. Furthermore, the dose-effect curve derived from the laboratory investigations lies significantly above that derived from the field studies. At the lower end of the scale, the predicted amount of annoyed people is nearly the same (12% to 15%). At the far end, 30% of the field population was annoyed, whereas in the laboratory population this proportion was 70%. Thus, the subjects in the laboratory were significantly more annoyed than those in the field.
The differences between laboratory and field results resembled those acquainted from the probabilities of awakenings induced by aircraft noise (Fig 2). They support the conclusion that nocturnal aircraft noise scenarios encountered in the field have much lesser effects than those experienced in the laboratory.
Further results are presented in a DLR research report [11].

3.3. Dose-response relations for stress hormones induced by aircraft noise during sleep

As an example, Fig 5 shows the box plots of nocturnal urinary noradrenaline excretion rates depending on the L_{eq} level during the nights. Shown are the results of the experimental groups in the laboratory without nights 1, 12, and 13 having been adaptation and recovery nights without aircraft noise. Baseline night 2 was also noise free (≤ 30 dB). The results are given in light boxes. The results from the field studies are indicated in grey boxes. Here, the first night is omitted as adaptation night. Normal range for noradrenaline excretion in urine (adults, HPLC method) is 10 – 55 ng/min (calculated from 24 h excretion [13]).
The F-test applied to the data of the laboratory experimental group of 112 subjects showed that at least one of the L_{eq} classes differs statistically significant from the noradrenaline excretion during baseline nights ($F = 13.16$ and $p = 0.001$). The mixed model estimated for noradrenaline excretions during the baseline nights a mean ± SE = 16.1 ± 0.5 ng/min and for the pooled data of noisy nights a lower mean ± SE = 14.9 ± 0.5 ng/min. Post-hoc tests revealed that the noradrenaline excretion rates in L_{eq} classes 30 ≤ 33 dB (14.8 ± 0.5 ng/min), 33 ≤ 36 dB (14.7 ± 0.5 ng/min), 39 ≤ 42 dB (14.8 ± 0.6 ng/min) 48 ≤ 51 dB (14.6 ± 0.6 ng/min), and > 51 dB (13.9 ± 0.8 ng/min) were significantly lower than in the baseline group L_{eq} ≤ 30 dB. A univariable regression analysis indicated a statistically non significant of the noradrenaline excretion rate depending on L_{eq} ($p = 0.895$; 0.002 ng/min per 1 dB increase L_{eq}).
The F-test applied to the data of the field group of 64 subjects stated that there was no significant difference in noradrenaline excretions during reference nights with an L_{eq} ≤ 30 dB compared to pooled data of nights with L_{eq} > 30 dB ($F = 0.04$ and $p = 0.836$) The mixed model estimated for noradrenaline excretions during the quiet

nights a mean ± SE = 15.1 ± 0.7 ng/min and for the pooled data of nights with L_{eq} > 30 dB a mean ± SE = 15.2 ± 0.6 ng/min. A univariable regression analysis indicated a statistically non significant and irrelevant decrease of the noradrenaline excretion rate depending on L_{eq} (p = 0.640; 0.02 ng/min per 1 dB increase L_{eq}).

Thus, for noradrenalin, as well as for all other stress hormone (adrenalin, cortisol) and electrolytes excretions under investigation dose-response relations could not be established. These results are in contrast to the findings of clear dose-response relationships for noise-induced awakenings and noise-related annoyance.

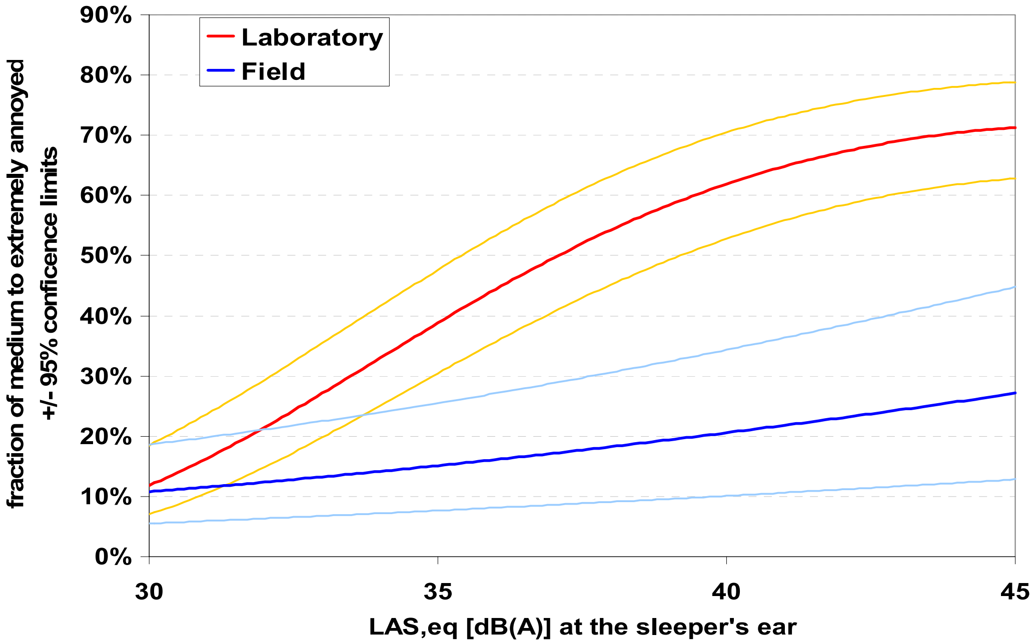

FIG 4. Group of people highly or moderate annoyed by aircraft noise (categories ≥ 3) under field and laboratory conditions, depending upon equivalent noise levels $L_{AS,eq}$ (“at sleeper´s ear”).

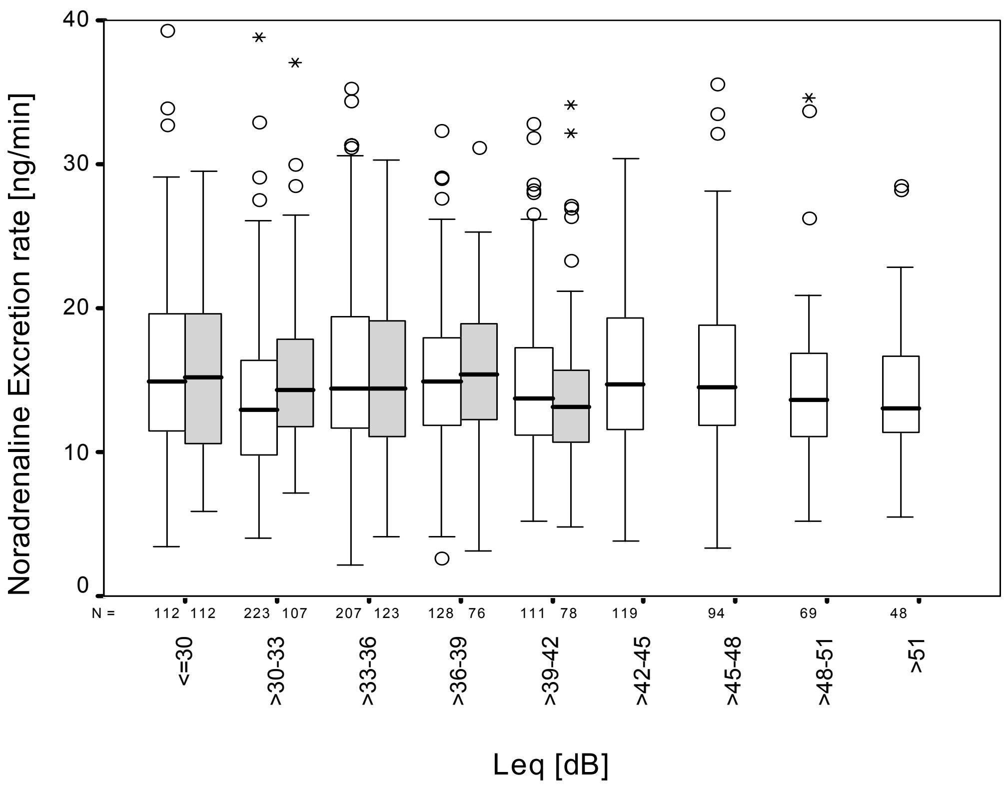

FIG 5. Box plot of the noradrenaline excretion rates in all night urine samples during both laboratory (light boxes) and field (grey boxes) studies depending on L_{eq} classes during the nights. Laboratory studies comprise experimental groups only, with nights 2 – 11, field studies with nights 2 - 9. N refers to the number of investigated nights.

4. SUMMARY AND DISCUSSION

The DLR-Institute of Aerospace Medicine investigated various physiological and psychological effects of night aircraft noise on a large population. This investigation was conducted with 192 subjects in 2240 nights. Laboratory and field studies were performed using the same extensive and expensive methods, including acoustical, polysomnographical, biochemical, and psychological methods as well as performance tests.

Dose-response curves were established for aircraft noise-induced awakenings during sleep and for aircraft noise-induced annoyance. In addition, a threshold for aircraft noise-related awakenings at 33 dB(A) was also found. Neither stress hormone and electrolyte excretion showed a relationship with noise levels, nor subjective ratings of fatigue, mood, sleep quality and quantity.

Based on the polysomnographic results, recommendations were formulated for legal and administrative purposes in Germany. These recommendations were applied for a night protection concept at a German airport (airport Leipzig/Halle) which is extended as a hub for the cargo and service provider DHL. These recommendations will be presented in a separate contribution to this conference [3] and have been recently published [4].

5. ACKNOWLEDGMENTS

The work was carried out within the DLR-research project „Quiet Air Traffic“ and was partially funded by the Helmholtz Association of National Research Centers. Many subjects volunteered in the laboratory and field studies. Especially we acknowledge those volunteers who participated in their own homes and gave the investigators permission to access and to intrude into their private spheres. Without the help of numerous assiduous colleagues of the Flight Physiology Department who sacrificed several weekends and tolerated countless sleepless nights, this study would not have been possible.

6. REFERENCES

[1] Babisch, W. Stress hormones in the research on cardiovascular effects of noise. Noise & Health 2003

[2] Basner M., Buess, H., Elmenhorst, D. et al.: Aircraft Noise Effects Volume 1: Executive Summary. Deutsches Zentrum für Luft- und Raumfahrt, Köln, Forschungsbericht 2004-07/E (2004)

[3] Basner M., Samel A., Isermann U. Aircraft noise effects on sleep: DLR research and application. Proc. 34rd Inter-Noise 2006 Congress “Engineering a Quieter World”, Honolulu, December 3-5, 2006, paper N° 500

[4] Basner M., Samel A., Isermann U. Aircraft noise effects on sleep: Application of the results of a large polysomnographic field study. Journal of the Acoustical Society of America 119: 2772–2784 (2006)

[5] Hume, K. and Whitehead, C. Sleep disturbance due to introduced aircraft noise. In: Proceedings of the 8th International Congress on Noise as a Public Health Problem. Editors: de Jong, R. G., Houtgast, T., Franssen, E. A. M., and Hofman, W., Schiedam, The Netherlands (2003): 199-200

[6] Jansen, G. Gesundheitliche Wirkungen von Umweltlärm. Zeitschrift für Lärmbekämpfung 47: 103-107 (2000)

[7] Maaß, H. & Basner, M. Effects of Nocturnal Aircraft Noise Volume 3: Stress Hormones. Deutsches Zentrum für Luft- und Raumfahrt, Köln, Forschungsbericht 2004-09/E (2006)

[8] Miedema, H.M.E. and Vos, H., Exposure-response relationships for transportation noise. Journal of the Acoustical Society of America 104: 3432–3445 (1998)

[9] Pearsons K et al.: Predicting noise-induced sleep disturbance. Journal of the Acoustical Society of America 97:331-338 (1995)

[10] Rechtschaffen, A. et al.: A Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects. Washington, D.C., Public Health Service, U.S. Government, Printing Office (1968)

[11] Quehl, J. Effects of Nocturnal Aircraft Noise Volume 4: Psychological Effects. Deutsches Zentrum für Luft- und Raumfahrt, Köln, Forschungsbericht 2004-10/E (2005)

[12] Schultz, T.J., Synthesis of social surveys on noise annoyance. Journal of the Acoustical Society of America 64: 377–405 (1978)

[13] Tietz, N.W. (ed.): Clinical guide to laboratory tests. 3rd edition. W.B. Saunders Company, Philadelphia, PA (1995)