Cross-country comparison of aircraft noise-induced sleep disturbance

Sarah McGuire[1], Uwe Müller[2], Eva-Maria Elmenhorst[2], Franco Mendolia[2], Daniel Aeschbach[2], Mathias Basner[1]

[1] Division of Sleep and Chronobiology, Department of Psychiatry, University of Pennsylvania Perelman School of Medicine, Philadelphia, PA, USA

[2] Division of Flight Physiology, Institute of Aerospace Medicine, German Aerospace Center DLR, Cologne, Germany

Corresponding author's e-mail address: basner@upenn.edu

ABSTRACT

To inform policy, exposure-response relationships for aircraft noise-induced sleep disturbance are needed. Due to different nighttime airport operational patterns it has been unknown whether results from individual studies can be applied to other airports. In addition, there may be inter-cultural differences that affect an individual's sensitivity to awakening. To examine whether there are cross-country differences in aircraft noise-induced awakenings, results from 3 studies that obtained objective sleep and noise measurements were compared. Two of the studies were conducted in Germany and include the STRAIN study conducted near Cologne/Bonn airport (N=64) and data from three years of the NORAH study conducted near Frankfurt airport (year 1 N=49; year 2 N=83; year 3 N=187). The third study was conducted in the United States near Philadelphia International airport (N=37). Awakenings were identified based on ECG and actigraphy measurements using an automatic algorithm, enabling consistency in scoring across the three studies. Models relating awakenings to the indoor maximum noise level of single aircraft events were derived. Similarities and differences in the regressions of the 3 studies are discussed.

INTRODUCTION

To inform future considerations regarding noise and sleep disturbance, ideally there is one exposure-response curve that can be used across all airports within a country. Most existing models, for the probability of awakening, though either only include the maximum noise level as an explanatory variable or have a linear dependence on time. It is unclear whether these models can be applied to all airports, including those with nighttime noise curfews or airports with increased cargo operations at night, as the timing of these events could differentially affect sleep.

It is also unclear whether inter-cultural differences would limit the application of models across countries. Different housing types could affect not just the noise level but spectral content; it has been found that energy in the 31.5 Hz, 500 Hz, 4 kHz, and 8 kHz octave bands can lead to increased awakenings [1]. A survey on neighborhood noise conducted in Japan, Germany, USA, China, and Turkey, found that those living in the USA more easily adapted to noise then participants living in the other countries [2]. Differences in attitudes to noise could also affect the probability of awakening, Elmenhorst et al. [3] found that individuals with negative attitudes toward air traffic at Frankfurt Airport in 2012 took longer to fall asleep, and also spent more time awake after sleep onset; however the direction of causality is unclear. Also normal sleep patterns have been found in some studies to be related to ethnicity. Rao et al. [4] found African-American men had less deep sleep than Caucasian, Hispanic, or Asian men, which could in turn increase susceptibility to environmental factors.

To examine whether there are differences in the effect of aircraft noise on objectively measured awakenings between airports with different traffic patterns and countries, results from three studies were compared. Two of the studies were conducted in Germany around Cologne-Bonn Airport (STRAIN Study) [5] and Frankfurt Airport (NORAH Study). The third study was conducted in the United States near Philadelphia Airport. In all studies ECG and actigraphy measurements were obtained. Awakenings were identified based on increases in heart rate and body movement using an automatic algorithm [6]. Regression models relating the probability of awakening to the indoor maximum noise level of the events were derived; similarities and differences of the models are discussed.

METHODOLOGY

Study Descriptions

The Philadelphia International Airport (PHL) study was conducted by the University of Pennsylvania between July 2014 and July 2015 and had 39 participants that were exposed to aircraft noise (average age 46 years, 41% Male). It was a three night study, in which participants completed unattended measurements including ECG and actigraphy at night. The STRAIN and NORAH studies were conducted by the German Aerospace Center (DLR) around Cologne-Bonn Airport and Frankfurt Airport, respectively. The STRAIN study was conducted between September 2001 and November 2002, and had 64 participants (average age 38 years, 44% male). Subjects participated for nine consecutive nights. The NORAH study was conducted between July 2011 and November 2013. There were 49 participants in 2011 (average age 41 years, 49% Male), 83 in 2012 (average age 43 years, 41% Male), and 187 in 2013 (average age 40 years, 43% Male). The NORAH study in 2011 was conducted before a ban on nighttime flights between 23:00-5:00, and the studies in 2012 and 2013 were conducted after the ban. Participants completed measurements for three consecutive nights. The STRAIN study and NORAH 2011 and 2012 studies used polysomnography, which included ECG and body movement measurements. In NORAH 2013, similar to the PHL study, only ECG and actigraphy were measured.

Acoustic Analysis

In all studies the indoor noise levels were measured near the sleeper's ear using class one sound level meters. Sound recordings of aircraft events were listened to and systematically labeled. Only aircraft events that were undisturbed (i.e., noise from another source was not co-occurring), were included in the analysis.

Awakening Analysis

Awakenings during the night were identified automatically based on heart rate and actigraphy data. The program used for detection is based on the algorithm of Basner et al. [6] which identified EEG arousals ≥3 seconds based on heart rate alone. This algorithm was refined to identify EEG arousals ≥15 seconds using heart rate and actigraphy data [7], which is the minimum duration required for the classification of an awakening [8]. EEG arousals ≥15 seconds are a more specific indicator of noise-induced sleep disturbance than shorter EEG arousals due to the lower frequency of occurrence during nights without noise exposure. EEG arousals ≥15 seconds are identified in the algorithm by using matrices of likelihood ratios which indicate whether the difference in the beat to beat heart rate to a 3 minute median heart rate or the amount of movement is associated with an EEG arousals ≥15 seconds. For simplification, these vegetative-motoric reactions are referred to as awakenings below. Artifacts in the heart rate signals were visually identified, and these periods were removed from analysis. A 90-second time window was screened for awakenings after the start of an aircraft noise event, and no awakening reaction could occur within 15 seconds prior to the start of the aircraft noise event to be included in the analysis.

The spontaneous awakening probability (i.e., the probability of awakenings during noise-free periods) was also calculated by screening a period of 90 seconds from the start of virtual events for awakening reactions. Virtual events (i.e., periods of identical duration as the aircraft noise events but without aircraft noise) were assigned randomly to time periods within 30 minutes of an aircraft event within the other nights of the same subject during periods without aircraft or other noise events. The spontaneous probability ranged from 9.3% to 12.9% across the studies.

Statistical Analysis

Statistical analysis was performed using SAS (version 9.3, SAS Institute, Carey, NC). Random intercept logistic regression models were calculated for the probability of awakening to an aircraft.

RESULTS

The distribution of aircraft events included in the awakening analysis for each of the studies is shown in Figure 1. All airports and studies had different night-time traffic patterns. Philadelphia airport has cargo flights between 3:00 and 4:00, Cologne-Bonn had an increase in flights between 23:00 and 1:00 and 3:00 and 5:00, and in NORAH year 2012 and 2013 there was a ban on flights between 23:00 to 5:00 but with numerous movements in the shoulder hours.

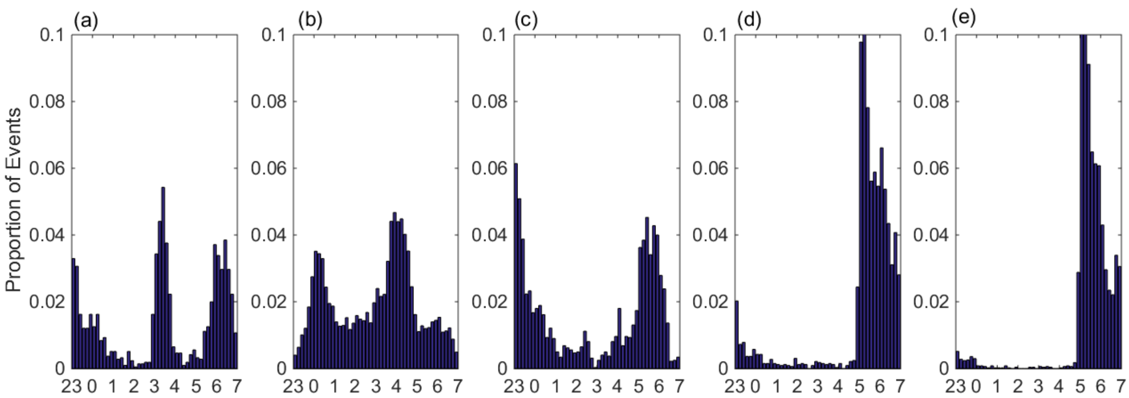

Figure 1: Distribution of aircraft events included in the analysis for (a) Philadelphia Airport Study, (b) STRAIN Study, Cologne-Bonn Airport, (c) NORAH Study 2011, Frankfurt Airport, (d) NORAH Study 2012, Frankfurt Airport, (e) NORAH Study 2013, Frankfurt Airport.

Random intercept logistic regression models were calculated for the probability of awakening to an aircraft event separately for each study. The spontaneous awakening probability was subtracted from the results to obtain the probability of an additional awakening [9]. The only explanatory variable in the model was the indoor maximum noise level L_{Amax}. The results are shown in Figure 2. The onset of additional awakenings ranged from 33 to 41 dBA. The increase in awakening probability with the indoor maximum noise level was comparable, with significant overlap in the confidence intervals.

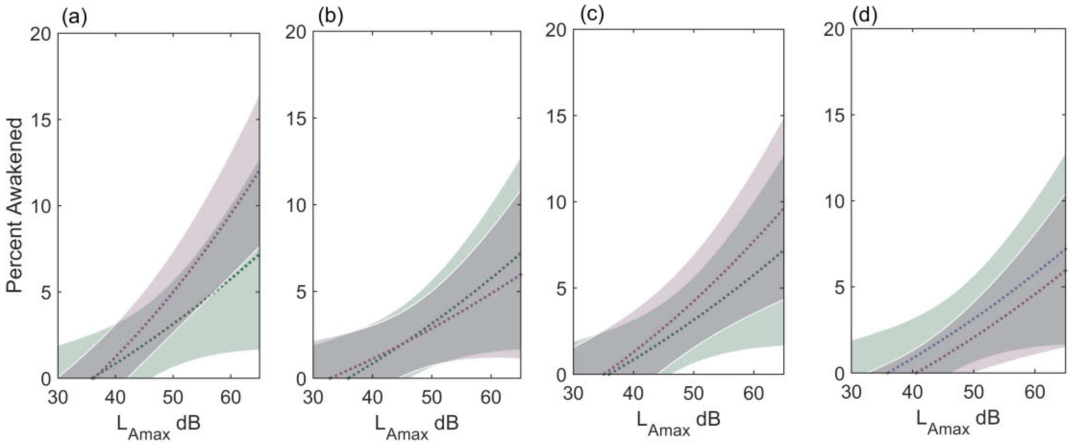

Figure 2: The unadjusted probability of an additional awakening within a 90 second time window from the start of an aircraft event. The Philadelphia International Airport (PHL) pilot study (green) is compared to the probability of awakening of (a) the STRAIN, (b) NORAH 2011, (c) NORAH 2012, and (d) NORAH 2013 studies (red).

Random intercept logistic regression models were calculated for the probability of awakening to an aircraft event adjusted for age, gender and time from sleep onset. The results are in Table 1.

Table 1: Logistic Regression model adjusted for age, gender, and time from sleep onset

	L_{ASmax} (dB)		Age		Male		Time (min)	
	Estimate (SE)	**p-value**	**Estimate (SE)**	**p-value**	**Estimate (SE)**	**p-value**	**Estimate (SE)**	**p-value**
PHL	0.020 (0.007)	0.013	-0.010 (0.005)	0.046	0.272 (0.163)	0.101	0.001 (0.0003)	0.004
STRAIN	0.025 (0.004)	<0.001	-0.018 (0.005)	0.001	0.073 (0.131)	0.582	0.002 (0.0002)	<0.001
NORAH 2011	0.023 (0.008)	0.008	-0.012 (0.005)	0.014	0.466 (0.149)	0.003	0.002 (0.0003)	<0.001
NORAH 2012	0.022 (0.006)	<0.001	-0.018 (0.006)	0.002	0.574 (0.163)	<0.001	0.002 (0.0004)	<0.001
NORAH 2013	0.018 (0.006)	0.001	-0.014 (0.004)	0.001	0.131 (0.124)	0.291	0.002 (0.0003)	<0.001

For all studies a significant effect for age and time from sleep onset was found. For three of the studies (PHL, NORAH 2011, and NORAH 2012) a significant effect for gender was also found with male participants having a higher probability of awakening.

DISCUSSION

Despite different airport flight operation patterns and the studies being conducted in different countries there was consistency in the probability of awakening across the three studies examined, with similar awakening thresholds between 33 to 41 dBA, similar increases in probability of awakening with noise level and with time from sleep onset. The decrease in probability of awakening with age while consistent was unexpected as sleep lightens and becomes more fragmented with age. This finding is likely related to age-related changes in the cardiovascular response to noise. In a laboratory study on the effects of traffic noise on sleep, Basner et al. [1] found a non-significant increase in noise-induced awakening probability, a significant increase in noise-induced EEG arousal probability, but a significant decrease in noise-induced changes in heart rate. Thus, the algorithm used for identifying awakenings in this analysis may be less sensitive for older participants, and further refinement may be needed. In addition, this study is limited as results were only compared between 3 airports and 2 countries, with the US study being a pilot field study not powered to derive a precise exposure-response function. In order to draw conclusions on the consistency of exposure response curves across airports and cultures, additional studies using objective measures of sleep are needed.

Acknowledgements

The Philadelphia International Airport study was funded by the U.S. Federal Aviation Administration (FAA) Office of Environment and Energy as a part of ASCENT Project 17 under FAA Award Numbers: 13-C-AJFE-UPENN-001 and 13-C-AJFE-UPENN-002. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA or other ASCENT Sponsors. We would also like to thank the Gemeinnützige Umwelthaus GmbH / Forum Flughafen & Region (Environment and Community Center / Forum Airport and Region), Kelsterbach, Germany for providing the funding for the NORAH study.

REFERENCES

[1] Basner, M., Müller U., & Elmenhorst, E-M. (2011). Single and combined effects of air, road, and rail traffic noise on sleep and recuperation. *SLEEP*, 34(1), 11-23.

[2] Namba, S., Kuwano, S., Schick, A., Aclar, A., Florentine, M., & Da Rui, Z. (1991). A cross-cultural study on noise problems: comparison of the results obtained in Japan, West Germany, the USA, China, and Turkey. *Journal of Sound and Vibration,* 1991, 151(3), 471-477.

[3] Elmenhorst, E-M., Müller, U., Mendolia, F., Quehl, J., & Aeschbach, D. (2016). *Resident's attitude towards air traffic and objective sleep quality are related*. Paper presented Internoise 2016, Hamburg, Germany.

[4] Rao, U., Poland, R. E., Lutchmansingh, P., Ott, G. E., McCracken, J. T., & Ming Lin K. (1999). Relationship between ethnicity and sleep patterns in normal controls: implications for psychopathology and treatment. *Journal of Psychiatric Research,* 33, 419-426.

[5] Basner, M., Isermann, U., & Samel, A. (2006). Aircraft noise effects on sleep: Application of the results of a large polysomnographic field study. *The Journal of the Acoustical Society of America*, 119(5), 2772-84.

[6] Basner, M., Griefahn, B., Müller, U., Plath, G., & Samel, A. (2007). An ECG-based algorithm for the automatic identification of autonomic activations associated with cortical arousal. *Sleep*, 30(10),1349-1361.

[7] McGuire, S., Müller, U., Plath, G., & Basner, M. (2014). *Refinement and validation of an ECG based algorithm for detecting awakenings*. Paper presented at the 11th International Congress on Noise as a Public Health Problem (ICBEN), Nara, Japan.

[8] Iber, C., Ancoli-Israel, S., Chesson, A., Quan, S. F. (2007). The AASM manual for the scoring of sleep and associated events: rules, terminology and technical specifications. Westchester, Illinois: American Academy of Sleep Medicine.

[9] Brink, M., Basner, M., Schierz, C., Spreng, M., Schuech, K., Bauer, G., Stahel, W. A. (2009). Determining physiological reaction probabilities to noise events during sleep. *Somnologie,* 13, 236-243.