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ORIGINAL ARTICLE

Short-term annoyance from nocturnal aircraft noise exposure: results of the NORAH and STRAIN sleep studies

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Abstract

Purpose The German Aerospace Center (DLR) investigated in the NORAH sleep study the association between a distinct change in nocturnal aircraft noise exposure due to the introduction of a night curfew (11:00 p.m.–5:00 a.m.) at Frankfurt Airport and short-term annoyance reactions of residents in the surrounding community. Exposure–response curves were calculated by random effects logistic regression to evaluate the aircraft noise-related parameters (1) number of overflights and (2) energy equivalent noise level L_{ASeq} for the prediction of short-term annoyance. Data of the NORAH sleep study were compared with the STRAIN sleep study which was conducted by DLR near Cologne–Bonn Airport in 2001/2002 ($N = 64$), representing a steady-state/low-rate change.

Methods The NORAH sleep study was based on questionnaire surveys with 187 residents living in the vicinity of Frankfurt Airport. Noise-induced short-term annoyance and related non-acoustical variables were assessed. Nocturnal aircraft noise exposure was measured inside the residents' home.

Results A statistically significant rise in the portion of annoyed residents with increasing number of overflights was found. Similarly, the portion of annoyed subjects increased with rising L_{ASeq}. Importance of the frequency of fly-overs for the prediction of annoyance reactions was emphasized. The annoyance probability was significantly higher in the NORAH than in the STRAIN sleep study.

Conclusions Results confirm the importance of both acoustical parameters for the prediction of short-term annoyance due to nocturnal aircraft noise. Quantitative annoyance models that were derived at steady-state/low-rate change airports cannot be directly applied to airports that underwent a distinct change in operational and noise exposure patterns.

Keywords Nocturnal aircraft noise · Night curfew · Airport change study · Annoyance · Sleep · Exposure–response curves

Introduction

About half of the residents in the European Union live in regions where their acoustical comfort and well-being is impaired due to the impact of different traffic noises (WHO 1999, 2009). Effects of noise exposure on humans are very complex and a variety of potential health-related effects of traffic noise on the population have been described in the available literature, including cardiovascular and other physiological effects, sleep disturbance as well as psychological effects on communication, cognitive performance, residential behavior and annoyance. Annoyance is regarded as the most important psychological impact of traffic noise exposure (Guski et al. 1999, 2016; Hoeger et al. 2002; Kroesen and Schreckenberg 2011; Passchier-Vermeer and Passchier 2000; Stansfeld and Matheson 2003). Prior surveys of community annoyance have shown that especially the main traffic noise sources, i.e., street, railway and air traffic lead to annoyance of the population (Babisch et al. 2009; Gille et al. 2016; Guski 1987, 2001; Guski et al. 2016; Héritier et al. 2014; Ortscheid and Wende 2002a; Kastka 2001b, 2002b; Ragettli et al. 2016). In Germany, for

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instance, aircraft noise is the second most disturbing and annoying traffic noise source to residents, surpassed only by road traffic noise (Umweltbundesamt (UBA) 2015).

Unfortunately, to date, there is no common agreement in the research community on the exact definition of the term “noise annoyance”. Broadly, it is adopted that it describes a potentially negative factor for the physical, mental and social well-being of an individual and consequently is ranked below the threshold of direct health impairment (Kastka 2001a; WHO 1999). Annoyance mainly results from the disturbance of activities caused by noise (Ahrlin 1988; Hall et al. 1985). Activities such as communication, relaxation and recuperation are considered to be especially sensitive to disturbances (Guski 1987, 1999; Guski et al. 2016). The disturbance of sleep is one of the most common reasons for noise complaints (Halperin 2014; Muzet 2002; WHO 2009). The annoyance model of Porter et al. (2000) distinguishes different time dimensions of annoyance. While short-term annoyance relates to a limited time span, for instance, the previous night, long-term annoyance describes a general feeling that has evolved over longer periods of weeks, months or even years. Long-term annoyance is considered to result from the accumulation of acute physiological responses to a noise event (e.g., noise-induced awakenings) and short-term reactions the day after a disturbed night’s sleep. Bartels et al. (2015) found a moderate correlation between mean short-term annoyance and long-term annoyance ratings (see also Bartels 2014; Schreckenberg and Schuemer 2010).

Since annoyance is considered to be the most important psychological consequence of traffic noise exposure, in the past a variety of empirical studies have been conducted to develop valid exposure–response curves for the prediction of residents’ annoyance (Babisch et al. 2009; Fidell et al. 1991; Héritier et al. 2014; Janssen et al. 2011; Miedema and Oudshoorn 2001; Miedema and Vos 1999; Ragettli et al. 2016; Schreckenberg et al. 2010; Schultz 1978). Presently, the most widely accepted exposure–response curves for aircraft noise annoyance are those developed by Miedema and Oudshoorn (2001). Their curves were originally established to predict the annoyance from road traffic, aircraft and railways (separately for each noise source) and are used for noise assessment purposes by the European Commission (2002) (Environmental Noise Directive 2002/49/EC). In a recent study, Gille et al. (2016) revised the exposure–response curves proposed by Miedema and Oudshoorn (2001) for each traffic noise source. In general, for each traffic noise, these curves describe an increase in annoyance with rising exposure, depending on the underlying acoustical parameters to different degree (Björkman et al. 1992; Fields 1984, 1993; Rylander et al. 1972, 1980, 1986). Average noise levels are usually seen as the best available acoustical measure to reliably predict noise annoyance (Hellbrück 1993; Schick 1997). Accordingly, in many studies aircraft noise exposure is described by the (A-weighted) energy equivalent noise level (Aasvang and Engdahl 1999; Quehl and Basner 2006; Ragettli et al. 2016; Schreckenberg et al. 2010). However, field studies with residents affected by aircraft noise have shown that the aircraft noise annoyance for sound pressure levels above 55 dBA is generally underestimated by average energetic noise levels (Guski 2001; Kastka 2001a, b). In the last 5 decades, increasing needs for mobility and a rising demand for freight traffic were accompanied by a significant growth of air traffic. Aviation industry forecasts a worldwide increase of passenger air traffic of up to 6% per year, and for cargo traffic up to 5% per year for the coming 20 years (Boeing 2015). This strong increase, with a simultaneous reduction of the emission levels per aircraft, implies a significantly qualitative change of the aircraft noise exposure. Hence, in recent times residents affected by aircraft noise have reported that the noise has increased, since they refer to increased air traffic and shorter quiet periods between single overflights rather than relating their assessment to an average noise level. Therefore, Guski (1999) pointed out that noise affected persons do not only react to a global noise exposure, characterized by the average noise level, but rather to noise events, i.e., to number, distribution, duration, level, and meaning of noise exposure (see also Ising and Kruppa 2002). Annoyance ratings can differ extremely among residents of the same airport community and these differences cannot be solely explained by acoustical parameters such as loudness, frequency and duration of the noise exposure (Job 1988). There is ample evidence that noise annoyance is generated by a complex interaction of acoustical and non-acoustical variables (Fields 1993; Job 1988; Lercher 1996; Miedema and Vos 1999). A rule of thumb is that about one-third of annoyance is determined by acoustical factors, another third by non-acoustical factors, while the last third has not been defined yet (Bartels 2014; Bartels et al. 2013, 2015; Brink 2014; Fields 1993; Guski 1987, 1991, 1999, 2001; Hoeger 1999; Janssen et al. 2011; Job 1988; Miedema and Vos 1999; Oliva 1998; Schick 1997; Schuemer and Schuemer-Kohrs 1984; Stallen 1999). The individual noise sensitivity is an important personal variable (Gille et al. 2016; Job 1999; Miedema and Vos 1999, 2003; Stansfeld 1992; Weinstein 1978; Zimmer and Ellermeier 1999). There are variables related to aircraft noise specific contents (Bartels 2014; Bartels et al. 2015; Janssen et al. 2011; Kroesen et al. 2008; Miedema and Vos 1999; Oliva 1998; Ortscheid and Wende 2000). They include, for example, residents’ attitudes towards air traffic, their beliefs about how air traffic may affect them (including perceived social and economic advantages/disadvantages and its assessment regarding the harm to one’s health), negative expectations regarding future noise development at an airport, feelings of helplessness in controlling air traffic, perceived fairness and consideration of local residents' interests in decision-making with respect to the airport, adaptation to chronic aircraft noise exposure, and concerns about safety (e.g., fear of aircraft crashes).

The effects of traffic noise described in the available literature are mainly related to steady-state exposures, i.e., noise situations that have not significantly changed over a longer period of time, i.e., at least several months or even some years. The opening of a new runway or the temporal redistribution of (nocturnal) fly-overs according to new air traffic management may result in a step change, or abrupt change, to exposure from aircraft noise for residents in the surrounding community. In this context, Gjestland et al. (2015), Gjestland and Gelderblom (2017), Guski et al. (2016) as well as Janssen and Guski (2017, in press) suggested a further subdivision in "high-rate-of-change" (HRC) airports and "low-rate-of-change" (LRC) airports. At HRC airports large changes in operational patterns took place within the last 3 years or such major changes in the near future are expected, and/or extensive public debates and media interest on operational issues have emerged. LRC airports underwent only minor changes in operations and noise-related debates; gradual changes in noise exposure may result from growth in air traffic over several years. At both HRC and LRC airports no pure steady-state exposure is ever present. In general, airports with an abrupt or large change due to operational patterns were associated with higher daytime annoyance than steady-state/low-rate change airports at comparable noise levels (Guski et al. 2016).

Brown and van Kamp (2009a) have reviewed the literature available on human response to changes in traffic noise exposure (see also van Kamp and Brown 2003, 2009b). According to their review, the number of traffic noise change studies is small and they are not comparable in terms of method, size, and study design. It has been reported that reactions of residents to an increase or decrease in exposure may be different to that predicted from steady-state curves. Human response to change in exposure may include a change effect which establishes itself as an excess response: with increasing noise exposure, individuals are much more annoyed than would be predicted by steady-state curves, and with a decrease of exposure, residents are much less annoyed (Brink et al. 2008; Fields et al. 2000; Job and Hatfield 2003; Schreckenberg and Meis 2007; Schuemer and Schreckenberg 2000; van Kamp and Brown 2003). Brown and van Kamp (2009a) emphasized that an excess response is not necessarily a temporary appearance; rather it may persist years after change in exposure. There is no accepted explanation of the mechanism underlying the excess response phenomenon yet (see also Brown and van Kamp 2009b). Thus, results of aircraft noise change studies are inconclusive (Breugelmans et al. 2007; Fidell et al. 1996, 2002; Francois 1979; Kastka et al. 1995; Miyahara 1988). While Fidell et al. (2002) and Breugelmans et al. (2007) found large responses to change in aircraft noise exposure; the change effect in other airport change studies was very small. According to Brown and van Kamp (2009a) these small change effects are caused by the nature of the specific noise changes that took place at most of the examined change airports: commonly small, gradual, or temporary.

NORAH (Noise-Related Annoyance, Cognition, and Health) is the most extensive study on transportation noise impact in Germany so far (Forum Flughafen & Region, Umwelt- und Nachbarschaftshaus 2015). From 2011 to 2013 NORAH examined in five sub-studies the impact of aircraft, road and rail traffic noise on exposed population in the Rhine-Main area around Frankfurt Airport. For the introduction of a night curfew with a modified noise exposure pattern in the night-peak hours, there were no airport change studies available up to now. The German Aerospace Center (DLR) investigated in the NORAH sleep study the physiological and psychological impact of aircraft noise exposure before and after the opening of the northwest runway at Frankfurt Airport in October 2011 and the associated temporal redistribution of nocturnal overflights according to the new night curfew (11:00 p.m.–5:00 a.m.). The new air traffic management caused a "high-rate-of-change" (HRC) in aircraft noise exposure in the neighboring community (Gjestland et al. 2015; Gjestland and Gelderblom 2017; Guski et al. 2016; Janssen and Guski 2017, in press). The present paper presents the results of short-term annoyance of the affected residents following such a distinct change in nightly exposure from aircraft noise. Since acoustical factors play an important role for the degree of aircraft noise-induced short-term annoyance, the "number of overflights per night" and "energy equivalent noise level" were evaluated as predictors of short-term annoyance. For this purpose, exposure–response curves were calculated by means of random effects logistic regression. Whereas L_{ASeq} has usually been used to characterize the exposure–response relationship between aircraft noise and short-term annoyance, it was hypothesized that—due to the intermittent nature of aircraft noise—the number of nocturnal overflights may represent an equal or even better predictor of annoyance. Additionally, non-acoustical factors were taken into account because they may explain a considerable amount of the observed variance in annoyance reactions. A cross-sectional comparison of the short-term annoyance ratings measured in the NORAH sleep study with ratings of the STRAIN (Study on Human Specific Response to Aircraft Noise) sleep study conducted by DLR near Cologne–Bonn Airport in 2001/2002 ($N = 64$) was also performed. The Cologne–Bonn Airport belongs to the category of to steady-state or LRC airports with a high number of nocturnal flights, i.e., if at all, only minor changes in operations and related noise exposure were expected to be present during the study. It was hypothesized that there is a significant difference in aircraft noise-induced short-term annoyance reactions between the two sleep studies. Previous findings indicated that airports with a large change due to operational patterns were associated with higher (daytime) annoyance reactions than steady-state/low-rate change airports (Guski et al. 2016). A similar effect was expected in the present investigation.

Methods

Participants and study design

The NORAH sleep study was performed during three measurement periods from 2011 to 2013 in the Rhine-Main area around Frankfurt Airport before and after the opening of the new runway in October 2011 and the associated ban of night flights between 11:00 pm and 5:00 am. A total of 202 healthy adult airport residents was investigated. In 2011 and 2012, participants' nocturnal sleep was measured with polysomnography (PSG), whereas in 2013 measurements at night were limited to actigraphy and electrocardiogram (McGuire et al. 2016; Müller et al. 2015).

In the morning, participants rated their sleep quality, problems falling asleep, and acute fatigue. In the 2013 measurement campaign, short-term annoyance as measured on a five-point scale was added to the morning assessments.

Subjects were selected in a multi-stage selection process. A questionnaire was used to exclude persons with major medical or intrinsic sleeping disorders or working night shifts. Medical exclusion criteria included cardiac insufficiencies, periodic limb movements in sleep, obstructive sleep apnea syndrome, and chronic diseases such as migraine. In 2013 there was a total of 484 applications, from which 112 participants successfully passed the selection process. Thirty-nine subjects participated in all three measurement periods (i.e. 2011, 2012, 2013), 36 individuals participated in 2012 and 2013. Thus, a total of 187 healthy adult subjects (107 female) with normal hearing ability according to their age and suffering from no reported intrinsic sleep disorder were investigated in 2013. Age ranged from 18 to 78 years (mean (M) = 39.8, standard deviation (SD) = 15.4).

Subjects volunteered to participate in the study and gave written informed consent in accordance with the guidelines of the Declaration of Helsinki prior to the study. The subjects could terminate their participation at any time. Due to the complex physiological sleep measurements subjects received remuneration for their participation in the study.

The study was carried out from June to November 2013 at the residents' home for three consecutive nights. Measurements always started on a Monday. The bed time of the subjects corresponded to the usual sleep duration between 7.5 and 8.5 h in Central Europe (Schlack et al. 2013). During the measurement nights, participants could choose the window position (open, closed, tilted) in the bedroom they slept as they preferred. They were only asked to not change the window position during the night. In all nights, subjects' heart rate and motor activity were recorded to detect vegetative-motoric reactions to noise.

Acoustical measurements (exposure)

In all study nights, the sound pressure level and the sound files for the entire bed time of the participants were recorded continuously inside the bedroom at the sleeper's ear. Recordings were performed by a Class-1 sound level meter (XL2 from NTI) and an indoor microphone installed near the subject's ear. The sound pressure levels were logged with an A-weighting and a slow-response (LAS) in the interval of one second. For subsequent noise identifying wav files were consistently recorded with 24-kHz sampling rate. The A-weighted energy equivalent continuous sound pressure level related to subject's time in bed (L_{ASeq}) and number of nocturnal overflights were determined based on the acoustical measurements inside the bedroom.

The L_{ASeq} of all overflights ranged from 0 to 50 dBA, the median of the L_{ASeq} was 19 dBA. The mean frequency of nocturnal fly-overs ranged from 0 to 9.6 per hour (11:00 p.m.–7:00 a.m.) with SD ranging from 0.2 to 10.0 (Müller et al. 2015; Quehl et al. 2016).

Subjective measurements (response)

Short-term annoyance ratings were carried out retrospectively in the morning, approximately 15 min after wake-up, using survey software running on a netbook. Long-term annoyance from aircraft noise exposure was determined by paper and pencil surveys at the beginning of the study. Both, short-term and long-term annoyance were rated on a semantic five-point response scale ("1 = not" to "5 = very" annoyed). Information on personal and non-acoustical factors of noise annoyance was obtained by paper and pencil questionnaires after the study. Besides demographical data, the questions referred to the participant's noise sensitivity, the adaptation to chronic aircraft noise exposure, the general perception of loudness in the residential area, and chronotype. The chronotype describes the internal circadian rhythm of a person that influences the cycle of sleep and activity within a 24-h period. With exception of age, gender and chronotype, variables were measured by means of five-point answering scales (e.g., from "1 = not" to "5 = very"). Chronotype was determined using the German version of the Horne and Östberg Morningness–Eveningness questionnaire (1976), and Griefahn et al. (2001).

Statistical analysis

Random effects logistic regression was used to analyze the data. For the calculation of exposure–response curves, logistic regression analysis is an established approach in noise effects research (Brink et al. 2008; Keith et al. 2013; Matsui et al. 2004; Müller et al. 2015; Quehl and Basner 2005, 2006; Sung et al. 2016). Logistic regression analysis was used to estimate the probability to be (highly and moderately) annoyed by aircraft noise as a function of the different influencing (i.e., acoustical and non-acoustical) parameters. Like all regression analyses, the logistic regression is a predictive analysis. It is similar to linear regression analysis except that the dependent variable is binary, i.e., the dependent variable can be described as an event that either takes place (1) or does not take place (0). Thus, logistic regression is suitable to describe data and to explain the relationship between one dependent binary variable and one or more nominal, ordinal, interval or ratio-level independent variables. In the study each subject was asked repeatedly. Therefore, the random effects model accounted for the non-independency of annoyance ratings by including a random subject effect via a random intercept (Diggle et al. 2002). Additionally, a major advantage of the use of a random effects model was that information in differences both within subjects and between subjects was utilized.

For the present analysis, a binary variable was generated by the combination of the categories 3, 4 and 5 of the original annoyance five-point scale in order to take the range of "medium to high annoyance" into account (i.e., value 0 = "not and low annoyed", value = 1 "highly and moderately annoyed"). The Schultz criterion (Schultz 1978) defines persons, whose ratings are distributed in the upper 25 to 30% of an answering scale (e.g. on a five-point scale the categories 4 and 5) as "highly annoyed". However, the limitation on the portion of people who are highly annoyed by noise has the disadvantage that the (likewise quantitatively important) proportion of persons, whose noise annoyance falls in the middle part of the answering scale, is ignored.

Since both the energy equivalent noise level L_{ASeq} and the number of noise events are described in the literature as valid acoustical predictors of aircraft noise-induced annoyance the following parameters were integrated into the modeling:

(a) Acoustical factors

- Number of overflights per night.
- L_{ASeq} related to aircraft noise exposure during the time in bed.

(b) Non-acoustical factors

- Long-term annoyance due to aircraft noise ("1 = not" up to "5 = very annoyed by aircraft noise").
- Noise sensitivity ("1 = not" up to "5 = very sensitive to noise").
- Adaptation to chronic aircraft noise exposure ("1 = not" up to "5 = very adapted to aircraft noise").
- General perception of loudness in the residential area ("1 = not" up to "5 = very loud").
- Chronotype ("definite morning type" up to "definite evening type").
- Age.
- Gender.

To test the first hypothesis separate logistic regression models were developed for both acoustical parameters. With the exception of gender, all non-acoustical predictors were included as continuous variables into the models even though they were partially measured on an ordinal scale. The modeling was carried out using stepwise selection (Hosmer and Lemeshow 2000). The decision as to whether a variable was included or removed was based on the AIC (Akaike Information Criterion), which is a measure of the goodness of regression models (Pinheiro and Bates 2009). It describes the relative quality of a statistical model compared to two or a few a priori defined statistical models. Stepwise selection was continued until all factors proved to be significant and there was no improvement with respect to the AIC.

To account for possible non-linearity of the predictors, transformations of the variables were assessed for inclusion via the AIC. The aim was to analyze whether transformations, for instance, by quadratic and cubic terms or logarithmic transformations improved the model quality (Hosmer and Lemeshow 2000). Additionally, variables in the models were also tested for interactions and multicollinearity.

Logistic regression analysis was performed by the software package R (Version 3.1) (R Core Team 2014).

The final regression models are shown by tables. The statistical parameters should be interpreted as follows: the regression coefficient (i.e., estimate) is the estimated increase in the log odds of the response per unit increase in the value of the exposure. Positive coefficients indicate for every increase in the value of the exposure an increase in annoyance probability, holding all other variables in the model constant. Conversely, negative coefficients mean for each increase in the value of the exposure a decrease of the annoyance probability. The exponential function of the regression coefficient is the odds ratio (OR) linked with a one-unit increase in the exposure (Szumilas 2010). Thus, an OR describes the association between an exposure and a response. It represents the odds that a response (i.e., annoyance) will occur given a specific exposure, compared to the odds of the response occurring in the absence of that exposure. It applies that for OR values =1, there is no effect of exposure on odds of response, for OR values >1 the exposure is associated with higher odds, and for OR values <1 the exposure is related with lower odds. The 95% confidence interval (95% CI) is used to estimate the precision of the OR. A large CI indicates a low degree of precision, whereas a small CI indicates a higher precision.

Results

Short-term annoyance from nocturnal aircraft noise exposure in the NORAH sleep study

Descriptive statistics

Of the original sample with 187 subjects, only 157 persons could be considered in the data analysis. Thirteen subjects were excluded from analysis due to missing questionnaire data, 17 other persons were excluded due to missing acoustical measurements. There were a total of 443 annoyance ratings; 132 ratings were in the range of “highly and moderately annoyed” (categories 3–5 of the original five-point scale); 311 ratings were “not and low annoyed” (categories 1 and 2).

Figure 1 shows the percentage frequency distribution of the answer to the question “How much have you been annoyed by aircraft noise of the last night?” by using a five-point rating scale. As shown, about 70% of the subjects felt “not” or “little” annoyed. Twelve percent were “quite” or “very” annoyed, another 18% felt “moderately” annoyed.

With exception of age, gender and chronotype, ratings of non-acoustical factors ranged from 1 to 5 (long-term annoyance: M = 3.26, SD = 1.26; noise sensitivity: M = 3.0, SD = 0.70; adaptation to noise: M = 2.58, SD = 1.03; general perception of loudness: M = 2.57, SD = 0.74).

Exposure–response curves

The probability to be highly and moderately annoyed (categories ≥3) by aircraft noise of the previous night was modeled with a random effects logistic regression. The analysis resulted in two models presented in Tables 1 and 2 including the acoustical predictors (1) number of overflights (LR1) and the (2) energy equivalent noise level, L_{ASeq}, related to aircraft noise exposure during the time in bed (LR2), respectively, as well as the non-acoustical factors general perception of loudness in the residential area and adaptation to chronic aircraft noise exposure.

For all analyses, a significance level of 0.05 was assumed. Since the final *p* values of the regression parameters may be biased due to the model selection procedure (Harrell 2015), OR and the 95% CI are also given. The effect of a variable is regarded as significant when the OR

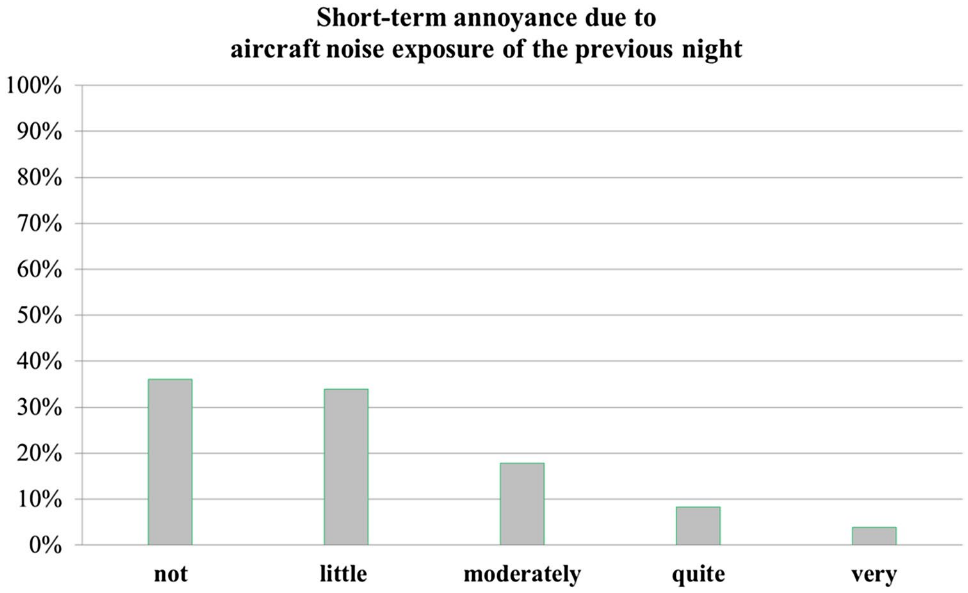

Fig. 1 Percentage distribution of aircraft noise-induced short-term annoyance due to exposure of the previous night ($N = 157$)

Table 1 Logistic regression model LR1 with random effects for the prediction of aircraft noise-induced short-term annoyance, depending on the number of overflights in the night

	Estimate	Standard error	*p* value	OR	OR 95% CI (lower)	OR 95% CI (upper)
Intercept	−2.176	1.001	0.030	0.114	0.012	0.811
Number of overflights	0.058	0.011	<0.001	1.060	1.036	1.089
Perception of loudness in the residential area	0.749	0.294	0.011	2.115	1.188	4.129
Adaptation to aircraft noise exposure	−0.993	0.231	<0.001	0.370	0.216	0.577

Results were partly published in the NORAH research report (Müller et al. 2015)

Table 2 Logistic regression model LR2 with random effects for the prediction of aircraft noise-induced short-term annoyance, depending on the energy equivalent noise level L_{ASeq}

	Estimate	Standard error	*p* value	OR	OR 95% CI (lower)	OR 95% CI (upper)
Intercept	−3.036	1.044	0.004	0.048	0.004	0.377
L_{ASeq}	0.086	0.020	<0.001	1.090	1.047	1.143
Perception of loudness in the residential area	0.887	0.293	0.002	2.428	1.362	4.823
Adaptation to aircraft noise exposure	−0.987	0.233	<0.001	0.373	0.216	0.582

Results were partly published in the NORAH research report (Müller et al. 2015)

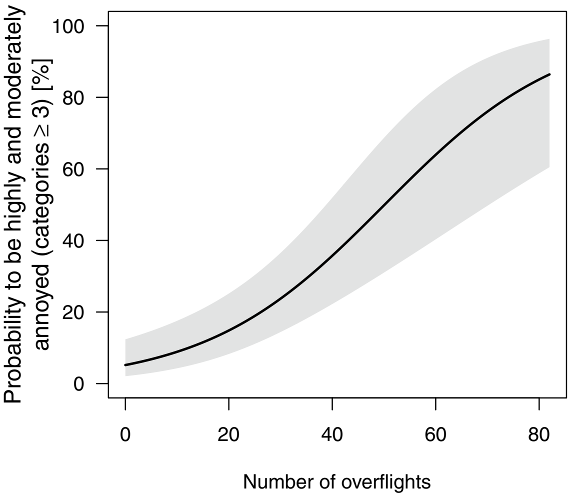

Fig. 2 Probability to be highly and moderately annoyed (categories $\geq$3) by aircraft noise of the previous night as predicted by the model LR1 depending on the number of overflights. The *gray area* shows the 95% confidence interval

is distinct from 1 (i.e., no effect) and when the 95% CI is not covering 1. As depicted by Table 1 the number of nocturnal overflights had a statistically significant effect on short-term annoyance ($p < 0.001$, OR = 1.060, 95% CI 1.036–1.089). The non-acoustical factors general perception of loudness in the residential area (positive regression coefficient) and adaptation to chronic aircraft noise exposure (negative regression coefficient) also proved to be statistically significant. This means that the subjectively perceived loudness in the residential area had a significant increasing effect on short-term annoyance from aircraft noise exposure ($p = 0.011$, OR = 2.115, 95% CI 1.188–4.129) while the adaptation to chronic aircraft noise exposure had a significant decreasing impact ($p < 0.001$, OR = 0.370, 95% CI 0.216–0.577). Thus, the percentage annoyed was significantly higher with lower aircraft noise adaptation. The OR is a useful measure to compare the effect sizes of the factors for the annoyance probability. Accordingly, the perception of loudness in the residential had a higher impact on annoyance probability than the adaptation to chronic aircraft noise exposure.

Figure 2 shows the percentage of subjects highly and moderately annoyed by aircraft noise depending on the number of nocturnal overflights predicted by model LR1. There was a statistically significant effect of number of overflights which resulted in an increase in annoyance probability with rising frequency of air traffic per night, reaching approximately 80% at 80 fly-overs per night (Table 1).

As depicted by Table 2 the L_{ASeq} had a statistically significant influence on short-term annoyance ($p < 0.001$). This was associated with an OR of 1.090 (95% CI 1.047–1.143). Again, the general perception of loudness in the residential area ($p = 0.002$, OR = 2.428, 95% CI 1.362–4.832) and the adaptation to chronic aircraft noise exposure ($p < 0.001$, OR = 0.373, 95% CI 0.216–0.582) played a significant role.

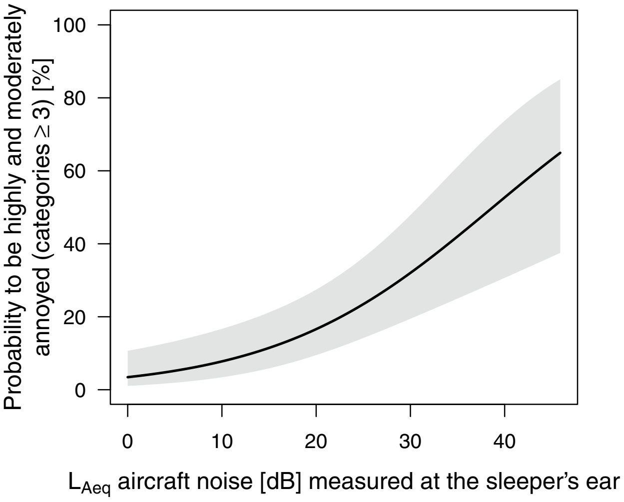

Fig. 3 Probability to be highly and moderately annoyed (categories ≥3) by aircraft noise of the previous night as predicted by the model LR2 depending on the energy equivalent noise level L_{ASeq}. The *gray area* shows the 95% confidence interval

Figure 3 depicts the probability of highly and moderately annoyed subjects with increasing energy equivalent noise level L_{ASeq} expected by model LR2. There was a significant increase of the proportion annoyed with rising L_{ASeq}, reaching approximately 60% at 50 dBA. For both figures, the non-acoustical variables were set to the median in the samples (i.e., general perception of loudness in the residential area =3, adaptation to chronic aircraft noise exposure =3).

Comparison of the NORAH and STRAIN sleep studies regarding short-term annoyance from nocturnal aircraft noise exposure

From 2001 to 2002 the DLR carried out the sleep study STRAIN in the vicinity of Cologne–Bonn Airport, one of the airports with the highest traffic densities at night, mainly caused by freight traffic. This sleep study was undertaken with 64 residents aged 19–61 years (35 female). Participants were studied at home under real-life conditions. The Cologne–Bonn Airport can be classified as steady-state or LRC airport, i.e., no distinct change in operations or noise exposure occurred during the STRAIN sleep study. The physiological, acoustical and subjective data corresponded to the measurements in the NORAH sleep study (Basner et al. 2006; Quehl and Basner 2005, 2006).

Data of the NORAH and STRAIN sleep studies were cross-sectionally compared in terms of exposure–response curves for short-term aircraft noise annoyance. For the development of logistic regression models data from the STRAIN sleep study were combined with those from the NORAH sleep study in 2013 to one data set. Two models were developed for the (1) number of overflights (LR3) and for the (2) energy equivalent noise level L_{ASeq} related to aircraft noise exposure during the time in bed (LR4). Non-acoustical factors were taken into account.

Tables 3 and 4 summarize the regression-based comparison of short-term aircraft noise annoyance measured in the NORAH sleep study and in the STRAIN sleep study. The differences between the sleep studies were statistically significant (LR3: $p < 0.001$, OR = 0.084, 95% CI 0.035–0.180; LR4: $p < 0.001$, OR = 0.148, 95% CI 0.065–0.307), indicating higher probability for increased annoyance at Frankfurt Airport than at Cologne–Bonn Airport. They are depicted in Figs. 4 and 5. For both figures, the non-acoustical variables were set to the median in the samples (i.e., age = 38 years, long-term aircraft noise annoyance =3, adaptation to chronic aircraft noise exposure =3). The probability to be moderately or highly annoyed increased with the rise in "L_{ASeq}" and the number of overflights. The data indicated that the annoyance probability in the NORAH sleep study was significantly higher than in the STRAIN sleep study.

In both LR3 and LR4, the adaptation to chronic aircraft noise exposure was again a significant non-acoustical

Table 3 Logistic regression model LR3 with random effects for the prediction of aircraft noise-induced short-term annoyance measured in the NORAH and STRAIN sleep studies, depending on the number of overflights in the night

	Estimate	Standard error	*p* value	OR	OR 95% CI (lower)	OR 95% CI (upper)
Intercept	−2.911	1.065	0.006	0.054	0.006	0.438
Study						
NORAH—sleep study 2013	0.000	Reference group		1.000	Reference group	
STRAIN—sleep study 2001/2002	−2.483	0.398	<0.001	0.084	0.035	0.180
Number of overflights	0.046	0.006	<0.001	1.047	1.034	1.062
Adaptation to aircraft noise exposure	−0.751	0.190	<0.001	0.472	0.317	0.680
Long-term aircraft noise annoyance	0.030	0.012	0.013	1.466	1.099	2.002
Age	0.382	0.147	0.009	1.030	1.006	1.056

Results were partly published in the NORAH research report (Müller et al. 2015)

Table 4 Logistic regression model LR4 with random effects for the prediction of aircraft noise-induced short-term annoyance measured in the NORAH and STRAIN sleep studies, depending on the energy equivalent noise level L_{ASeq}

	Estimate	Standard error	*p* value	OR	OR 95% CI (lower)	OR 95% CI (upper)
Intercept	−3.708	1.137	0.001	0.025	0.002	0.227
Study						
NORAH—sleep study 2013	0.000	Reference group		1.000	Reference group	
STRAIN—sleep study 2001/2002	−1.913	0.377	<0.001	0.148	0.065	0.307
L_{ASeq}	0.096	0.015	<0.001	1.100	1.066	1.140
Adaptation to aircraft noise exposure	−0.789	0.200	<0.001	0.454	0.297	0.668
Long-term aircraft noise annoyance	0.465	0.155	0.003	1.592	1.176	2.227
Age	0.021	0.013	0.095	1.021	0.996	1.048

Results were partly published in the NORAH research report (Müller et al. 2015)

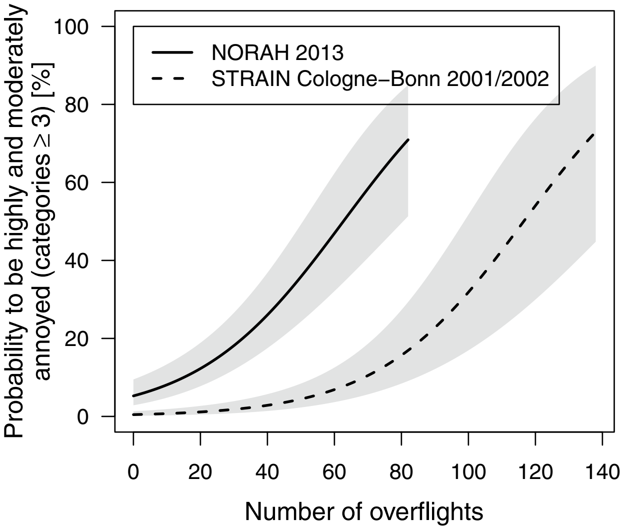

Fig. 4 Probability to be highly and moderately annoyed (categories ≥3) by aircraft noise of the previous night as predicted by the model LR3 depending on the number of overflights. The *gray areas* show the 95% confidence intervals

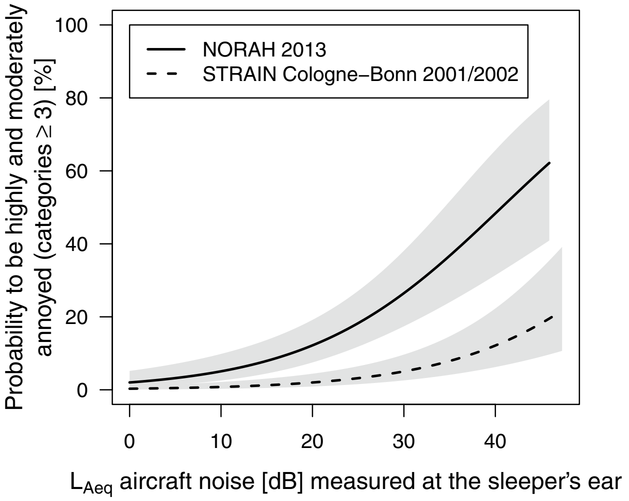

Fig. 5 Probability to be highly and moderately annoyed (categories ≥3) by aircraft noise of the previous night as predicted by the model LR4 depending on the energy equivalent noise level L_{ASeq}. The *gray areas* show the 95% confidence intervals

factor (LR3: $p < 0.001$, OR = 0.472, 95% CI 0.317–0.680; LR4: $p < 0.001$, OR = 0.454, 95% CI 0.297–0.668). The direction of effect of this non-acoustical variable remained the same as in the prior models. Furthermore, the long-term aircraft noise annoyance played a significant role (LR3: $p = 0.013$, OR = 1.466, 95% CI 1.099–2.002; LR4: $p = 0.003$, OR = 1.592, 95% CI 1.176–2.227).

Discussion

For the introduction of a night curfew with a modified noise exposure in the night-peak hours, there were no airport change studies available up to now. Due to the distinct change in operational patterns following the opening of the northwest runway at Frankfurt Airport and the associated temporal redistribution of nocturnal fly-overs according to the new night curfew from 11:00 p.m. to 5:00 the possibility to perform a HRC study was given (Gjestland et al. 2015; Gjestland and Gelderblom 2017; Guski et al. 2016; Janssen and Guski 2017, in press). The DLR examined the psychological impact of such a change in nightly aircraft noise exposure on short-term annoyance of 187 residents in the neighborhood of Frankfurt Airport.

In noise effects research, logistic regression is an established tool for the calculation of exposure–response curves (Brink et al. 2008; Keith et al. 2013; Ollerhead et al. 1992; Matsui et al. 2004; Müller et al. 2015; Quehl and Basner 2005, 2006; Sung et al. 2016). Exposure–response curves for aircraft noise-induced short-term annoyance were calculated by means of random effects logistic regression taking into account repeated measurements for the same subject. Separate models were developed for the (1) number of overflights (model LR1) and for the (2) energy equivalent noise level L_{ASeq} related to aircraft noise exposure during the time in bed (model LR2). Non-acoustical factors (i.e., noise sensitivity, adaptation to chronic aircraft noise exposure, long-term annoyance due to aircraft noise, general perception of loudness in the residential area, age, gender and chronotype) were also taken into account. The categories 3–5 of the original five-point annoyance scale (from "1 = not" to "5 = very" annoyed) were combined into one value according to a binary dependent variable. Thereby, subjects feeling moderately annoyed were considered additional to the portion of highly annoyed (Guski 2001; Jansen 1986; Rohrmann 1984; Schultz 1978).

According to the regression model LR1 that integrated the number of overflights as acoustical quantity, the percentage of persons moderately and highly annoyed by aircraft noise significantly grew with the increase of fly-overs. The percent of moderately and highly annoyed subjects rose with the frequency of fly-overs, reaching approximately 80% at 80 fly-overs per night. With an increasing number of overflights, the probability to consciously perceive air traffic during the times awake might simultaneously increase. This might disturb (intended) nightly activities such as sleep, and induce fatigue as well as negative emotional reactions. All this might be shifted in the focus of the participants' attention and can be better recalled. As a consequence, an increased degree of short-term annoyance in the following morning might occur (Quehl and Basner 2006). This explanation is supported by the theoretical annoyance model by Porter et al. (2000). It describes short-term annoyance in the morning as an aggregation of acute responses resulting from awakenings in the previous night and possibly perceived fatigue and cognitive performance decrements. The regression model LR2 described a statistically significant dependence of annoyance on the energy equivalent noise level L_{ASeq}. According to LR2, there was a significant rise in noise annoyance with increasing L_{ASeq} up to 60% at about 50 dBA.

Based on these findings the importance of the number of fly-overs for the prediction of short-term annoyance is emphasized again (Bartels et al. 2015; Quehl and Basner 2006). As hypothesized, aircraft noise exposure should not be judged exclusively on the basis of average energetic noise levels alone. According to the OR, the number of nocturnal overflight represents an equal predictor of annoyance. The disturbing effect of aircraft noise is primarily produced by individual overflights, i.e., residents do not react to global noise immissions, but they rather react to features of fly-overs such as their maximum levels, the duration of noise exposure and the number of (loud) aircrafts (Gjestland and Gelderblom 2017; Guski 1999, 2001; Ising and Kruppa 2002; Kastka 2001a, b). Accordingly, affected residents primarily complain about the increased frequency of overflights and the lack of noise-free periods between single fly-overs. Thus, noise metrics related to the number of overflights should also be taken into account when predicting short-term annoyance from (nocturnal) aircraft noise exposure. This may be of practical importance for the protection of airport local residents in terms of the definition of noise abatement zones and the specifications for affording domestic noise insulation. Besides, these results are important for operational approaches to minimize short-term annoyance due to aircraft noise in the affected airport communities. First of all, the decrease of overflight frequency together with the substitution of current (loud) aircraft by less noisy aircraft with higher transportation capacities seems to be an effective approach. However, decreasing the flight frequency through the use of fewer but bigger aircraft would entail fewer times of departure and, hence, reduces flexibility which is incompatible with the today's desire for an unrestricted mobility.

The findings also suggested a significant impact of non-acoustical factors on short-term annoyance from nocturnal aircraft noise exposure around Frankfurt Airport. The final regression models comprised the general perception of loudness in the residential area as well as the adaptation to chronic aircraft noise exposure as non-acoustical factors. Though personal variables are quite time-invariant and hence cannot account for differences within the ratings made by one person, it is assumed that they can lead to a general shift of short-term annoyance ratings towards a lower or a higher score (Bartels et al. 2015). Therefore, the consideration of these personal variables is relevant for the explanation of variance in short-term annoyance. In the present paper, the belief that one can adapt to the aircraft noise situation at home had a decreasing effect on the short-term annoyance (see also Quehl and Basner 2006). Adaptation to long-term noise exposure is an important feature in political discussions: whereas politicians and in part also residents exposed to chronic noise, for instance at major airports, are of the opinion that with time one can adapt to the noise and therefore better cope with it, studies suggest that high levels of annoyance do not decline over time and thus an adaptation to chronic noise exposure does not take place (Rohrmann 1974). In long-term studies the annoyance even increased during the course of time (Weinstein 1982). Stansfeld and Matheson (2003) emphasized that an adaptation to noise can be only achieved with a cost to health.

Results of the NORAH sleep study at Frankfurt Airport were cross-sectionally compared with aircraft noise-induced short-term annoyance measured in the STRAIN sleep study at Cologne–Bonn Airport in 2001/2002. Results indicated for both sleep studies that the proportion of those moderately and highly annoyed increased with the frequency of nocturnal overflights (model LR3) and the growth of the energy equivalent noise level L_{ASeq} (model LR4). Thereby, the relevance of noise metrics related to the frequency of fly-overs for the prediction of short-term annoyance from (nocturnal) aircraft noise exposure is stressed again. The significant non-acoustical factors in the different models were comparable (i.e., general perception of loudness in the residential area, adaptation to chronic aircraft noise exposure). Furthermore, the long-term aircraft noise annoyance played an important role. This finding is in accordance with previous studies which have shown that short-term annoyance and long-term annoyance judgments are directly related (Bartels 2014; Bartels et al. 2015; Schreckenberg and Schuemer 2010).

As hypothesized the annoyance probability in the NORAH sleep study was significantly higher than in the STRAIN sleep study. The residents investigated in the STRAIN sleep study were exposed to the aircraft noise situation at a LRC airport while the participants of the NORAH sleep study were exposed to the conditions at a HRC airport. Previous studies have shown that daytime short-term annoyance from aircraft noise was significant higher at HRC than at LRC airports (Gjestland et al. 2015; Gjestland and Gelderblom 2017; Guski et al. 2016; Janssen and Guski 2017, in press). Furthermore, a clear relationship between short-term annoyance and the number of aircraft movements at LRC airports was found, i.e., the annoyance probability increased with an increasing number of overflights. However, this dependency on frequency of aircraft movements could not be found for HRC airports. It is supposed that at this type of airports, the annoyance rating is most likely dominated by non-acoustical factors, and that the effect of number of aircraft seems to be lacking or even masked. The present findings showed a dependency of short-term annoyance from nocturnal aircraft noise on number of aircraft movements for both airport change classes. Differences in night-time aircraft noise exposure with respect to both the temporal distribution of the overflights (in the NORAH sleep study only in the peak hours, in the STRAIN sleep study continuous nocturnal flight operations) as well as the temporal distribution of the maximum noise levels at night might have contributed to this result.

The STRAIN sleep study was conducted in the period from 2001 to 2002. A meta-analysis of the available annoyance data of the previous 15 years performed by Guski et al. (2016) indicated that aircraft noise annoyance today is higher than shown by established "Miedema curves" (Miedema and Oudshoorn 2001). It is possible that the described gradual increase in daytime short-term annoyance also applied to short-term annoyance related to the night found in the NORAH sleep study (Guski 2004; Guski et al. 2016; Janssen et al. 2011; van Kempen and van Kamp 2005). However, there was no conclusive explanation of this trend up to now. It is assumed that both daytime and night-time short-term annoyance response to aircraft noise are influenced by a combination of acoustical and non-acoustical factors, and that airport specific situational matters determine which factors will dominate. It is concluded that the exposure–response curves that were derived at Cologne–Bonn Airport 2001/2002 cannot directly be applied to Frankfurt Airport, which due to the newly implemented night curfew showed a different noise exposure pattern in the night-peak hours.

In accordance with previous studies the results suggest that human response to change in traffic noise exposure does not correspond to what would be predicted by steady-state exposure–response curves. Further studies of change are urgently needed since most of the prior studies have shown significant methodological deficiencies. Only through careful design it will be possible to obtain valid empirical data and to understand and explain the nature of this phenomenon. This might emphasize the importance of assessing the impact of infrastructure changes and consequently might aid decision makers.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The NORAH sleep study was approved by the Ethics Committee of the Medical Association of North Rhine, and an informed written consent was required for participation in the study. All procedures performed in the study were in accordance with the ethical standards of this Ethical Committee and with the 1964 Helsinki declaration.

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