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The influence of acoustical and non-acoustical factors on short-term annoyance due to aircraft noise in the field — The COSMA study

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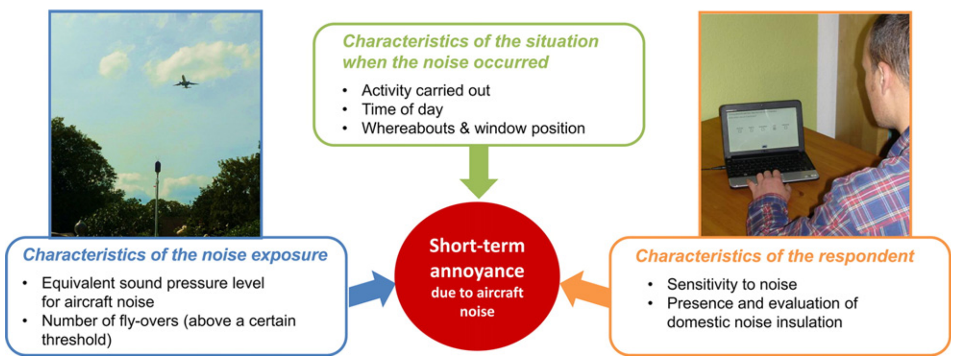
HIGHLIGHTS

- The equivalent outdoor sound level ($L_{Aeq,AC}$) slightly influences annoyance ratings.
- Number-related and individualized noise metrics improve the prediction of annoyance.
- Non-acoustics explain the same amount of variance as acoustics.
- The $L_{Aeq,AC}$ as only basis for noise abatement zones is questioned.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: Air traffic has increased for the past decades and is forecasted to continue to grow. Noise due to current airport operations can impair the physical and psychological well-being of airport residents.
Objectives: The field study investigated aircraft noise-induced short-term (i.e., within hourly intervals) annoyance in local residents near a busy airport. We aimed at examining the contribution of acoustical and non-acoustical factors to the annoyance rating.
Methods: Across four days from getting up till going to bed, 55 residents near Cologne/Bonn Airport ($M = 46$ years, $SD = 14$ years, 34 female) rated their annoyance due to aircraft noise at hourly intervals. For each participant and each hour, 26 noise metrics from outdoor measurements and further 6 individualized metrics that took into account the sound attenuation due to each person's whereabouts in and around their homes were obtained. Non-acoustical variables were differentiated into situational factors (time of day, performed activity during past hour, day of the week) and personal factors (e.g., sensitivity to noise, attitudes, domestic noise insulation). Generalized Estimation Equations were applied for the development of a prediction model for annoyance.
Results: Acoustical factors explained only a small proportion (13.7%) of the variance in the annoyance ratings. The number of fly-overs predicted annoyance better than did equivalent and maximum sound pressure levels. The proportion of explained variance in annoyance rose considerably (to 27.6%) when individualized noise metrics as well as situational and personal variables were included in the prediction model.
Conclusions: Consideration of noise metrics related to the number of fly-overs and individual adjustment of noise metrics can improve the prediction of short-term annoyance compared to models using equivalent outdoor

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levels only. Non-acoustical factors have remarkable impact not only on long-term annoyance as shown before but also on short-term annoyance judged in the home environment.

1. Introduction

Noise and noise-induced annoyance is a long-standing problem (Guski, 1987) that is accentuated during current times of increasing mobility and a rising need for transporting goods. According to an estimation of the World Health Organization, approximately half of the citizens in European Union countries live in "zones which do not ensure acoustical comfort to residents" because of ambient transportation noise (World Health Organization, 1999, p. 1). The number of aircraft noise events has increased dramatically in the past five decades going along with a significant reduction of the single aircraft event levels (IATA, 2012). For the coming 20 years, aircraft manufacturers forecast a worldwide growth of air traffic of up to 5% per year (AIRBUS, 2012; BOEING, 2014). However, it is not clear yet to what extent the sound pressure levels of single fly-overs can be decreased further.

This raises the question about the effects of aircraft noise in residential communities near airports. Besides health effects due to noise, annoyance is considered a major consequence of very high statistical evidence (Guski et al., 1999; Passchier-Vermeer & Passchier, 2000; Stansfeld & Matheson, 2003). According to the norm ISO/TS 15666 (ISO, 2003, p. 2), annoyance due to noise is "one person's individual adverse reaction to noise." This rather broad and non-specific definition is symptomatic for the fact that there is no consensus about the precise understanding of noise annoyance in the literature. In their empirical study with 68 international noise research experts, Guski et al. (1999) showed that the concept *noise annoyance* was associated highest with the terms nuisance, disturbance, unpleasantness, getting on one's nerves, interfering with intended activities, and irritation (p. 519).

Annoyance judgments (assumed to integrate the noise exposure over several months) vary remarkably among residents of the same airport community and these variations cannot be sufficiently explained by the equivalent sound pressure level, the L_{Aeq} (Job, 1988). Additional acoustical parameters, such as the number of (loud) events, maximum levels, the duration of noise exposure and repose times seem to have an effect on annoyance (Guski, 1999; Ising & Kruppa, 2002). However, prior surveys of community annoyance predominantly focused on a small range of aircraft noise indicators (Finke et al., 1975; Kroesen et al., 2008; Taylor, 1984; Wirth et al., 2004).

Besides exposure parameters, non-acoustical variables were found to play an important role in explaining long-term annoyance across, for instance, the past 12 months or for the general feeling of annoyance (e.g., Fields, 1993; Guski, 1999; Lercher, 1996; Miedema & Vos, 1999). Some of these non-acoustical variables refer to situational and contextual factors as, for instance, the time of day and the activity that was carried out when the individual was exposed to the aircraft noise. Evidence exists for the link between the disturbance of communicative activities and long-term annoyance (e.g., Ahrlin, 1988; Finke et al., 1975; Hall et al., 1985; Taylor, 1984). Furthermore, disturbance of sleep and recreation were found to be important determinants of long-term annoyance ratings (e.g., Ahrlin, 1988; Finke et al., 1975; Hall et al., 1985; Taylor, 1984). According to Hoeger (2004), a higher susceptibility to noise can be expected for the evening (≈18:00–22:00), at night (≈22:00–06:00), and in the early morning (≈06:00–08:00). These times of day are associated with activities such as aural communication as well as recreation and sleep that are prone to be disturbed or interrupted by noisy events (Fields, 1985). Similarly, during the weekend rest and relaxation prevail (Porter et al., 2000) and noise-susceptible activities are carried out (Fields, 1985). Consequently, noise exposure at the weekend evokes higher annoyance than equal noise exposure during working days (Schreckenberg & Meis, 2006).

In addition, there is ample evidence that personal and social factors contribute to noise-induced long-term annoyance and the general feeling of annoyance (Fields, 1993; Job, 1988; Lercher, 1996; Miedema & Vos, 1999). These factors include, e.g., the attitude towards the noise source and concerns about negative (health) effects of noise as well as personality traits, such as an individual's general sensitivity to noise or capacity to cope with noise (Kroesen et al., 2008; Miedema & Vos, 1999). A recent telephone survey at Cologne/Bonn Airport as well emphasized the impact of personal, social, and situational factors (Bartels et al., 2013). Annoyance rated for the past 12 months was associated with the L_{Aeq} calculated for the six months of the year with the highest air traffic volume as well as with the following non-acoustical predictors: a) the belief that the airport could take actions to improve the residents' situation, b) the judgment of negative aspects of the local airport and air traffic, c) carrying out measures to cope with the noise, d) the general attitude towards the airport, e) the satisfaction with the residential area, f) the respondent's environmental conscience, i.e., the prioritization of environmental versus economic aspects in aviation-related decision-making, g) the general sensitivity to noise as well as h) the degree of urbanization of the investigated areas, and i) the presence and evaluation of domestic noise insulation.

The findings reported in the preceding section all refer to annoyance judgments which are assumed to be integrating the noise exposure and annoyance over a longer time, at least several months. Whether and how exactly the exposure of the past months can be recalled and integrated is not completely clear yet. Therefore, attempts have been made to repeatedly assess single fly-over events and short periods of aircraft noise exposure in the field (e.g., Aasvang & Engdahl, 1999; Felscher-Suhr et al., 1996; Kastka et al., 1998; Schreckenberg & Meis, 2006; Stearns et al., 1983). But the number of studies doing so is very small. Seminal work on the influence of several aircraft noise indicators and non-acoustical factors on annoyance during the preceding hour in the course of the day was published by Schreckenberg et al. (Schreckenberg & Meis, 2006, 2007; Schreckenberg & Schuemer, 2010). But the authors likewise concentrated only on the most prominent metrics. These were the L_{Aeq} for aircraft noise during one hour, the number of fly-overs with a maximum above a certain threshold, the average sound pressure level above a certain threshold and maximum levels. Moreover, only outdoor levels were calculated. For indoor levels no estimates were available. Schreckenberg and Schuemer (2010) reported at best moderate correlations between one-hour annoyance judgments and the noise metrics listed above ($r \leq .42$). Moreover, the authors found that one-hour annoyance was (slightly) associated with the non-acoustical variables *noise sensitivity*, *concerns* and *negative expectations* concerning an extension of the airport and environmental/social problems as well as with the confidence in *authorities' effort for aircraft noise reduction*. However, a systematical examination of the effect of acoustical and non-acoustical factors on annoyance was not performed.

For a better understanding, in this paper *short-term* annoyance judgments over one or few hours are distinguished from *long-term* or *chronic* annoyance which describes a feeling that has been pent up over months and years. This distinction is made in the style of a theoretical model suggested by Porter et al. (2000), which was originally developed for the context of nocturnal annoyance. The model postulates higher levels of annoyance, i.e., *long-term annoyance*, as accumulations of lower levels of annoyance comprising *acute annoyance* reactions because of awakenings in the night and *short-term annoyance* the day after due to the perceived sleep disturbance and tiredness. According to Porter et al. (2000), all levels of annoyance have the same causes and share the same characteristics despite their different orders of time.

Although developed for nocturnal annoyance, the model seems to have relevance for daytime annoyance as well. Schreckenberg and Schuemer (2010) showed that mean short-term annoyance over the preceding hour was related to long-term annoyance over the past 12 months ($r = .53$). Moreover, for a subsample ($N = 48$) of the sample presented in this paper, Bartels (2014) found a correlation of $r = .50$ between mean short-term annoyance and long-term annoyance. The means differed significantly with higher scores for long-term annoyance ($d = 2.10$).

The present field study examined short-term annoyance as an important psychological consequence of aircraft noise exposure. The effects of aircraft noise on sleep, cognitive performance, and health have been investigated elsewhere in the recent past (sleep: e.g., Basner et al., 2008; Griefahn et al., 2006; cognitive performance: e.g., Elmenhorst et al., 2010; Hygge et al., 2002; Marks & Griefahn, 2007; health: e.g., Babisch et al., 2013; Black et al., 2007; Jarup et al., 2008).

Following the norm ISO/TS 15666 (2003) and the findings by Guski et al. (1999), we understand *annoyance* as a broad concept which is associated with, for instance, nuisance and irritation and not necessarily restricted to the disturbance or interference of (intended) activities. Therefore, we prefer to use the term *annoyance* instead of the more specific term *disturbance*. Our intention was to work up a comprehensive prediction model for short-term annoyance ratings which takes into account acoustical parameters as well as situation-related and personal factors. For this purpose, a wide range of noise metrics actually measured on-site and not only computed were set into relationship to annoyance judgments. Under the assumption that short-term annoyance reactions aggregate to long-term annoyance, the ultimate goal of the present study was to obtain new insights in the development of community annoyance.

2. Material and methods

2.1. Participants

Fifty-five healthy individuals (34 female) with normal hearing ability according to their age and an at least one-year-lasting residence at the examination site were studied. Age ranged from 18 to 70 years ($M = 46$, $SD = 14$). During the empirical study, 19 participants were unemployed and 32 individuals were employed, whereas four participants did not indicate their employment status. The mean duration of residence was 14 years ($SD = 10$, range = 2–54 years). 45 participants were homeowners. Participants were selected in a multi-stage selection process. A questionnaire was used to exclude individuals with major medical or intrinsic sleeping disorders or working night shifts. An audiometric test confirmed normal hearing threshold according to age. As a final step, a one-hour recording of the sound pressure level in the house was conducted to rule out that participants were exposed to major noise sources other than aircraft. Participants gave written informed consent and received an allowance of 250 € after completing the study.

2.2. Study design

The study was approved by the ethics board of the Chamber of Physicians North Rhine. The field study was conducted in the vicinity of Cologne/Bonn Airport which is an important German cargo hub operating 24 h a day with a busy period between 11 p.m. and 5 a.m. For four days and nights (not consecutive in each case), the outdoor sound pressure level (L_{AS}) was recorded continuously. During these four days, participants were instructed to repetitively rate their annoyance due to aircraft noise and to shortly characterize the context of the noise situation. This was carried out using survey software running on a netbook. The assessments were performed hourly from the time participants got up until they went to bed. A signal tone reminded the participants of the assessment task at the point of every hour. Two examination days were weekdays, the other two ones were Saturdays and Sundays. The hourly assessment presupposed staying at home or at least in the near neighborhood. Usual activities could be performed. The field study was conducted between June and November 2011 at 41 sites in two areas located 6 to 7.5 km north-west and south-east, respectively, of Cologne/Bonn Airport and close to the main flight paths. The long-term equivalent sound pressure level of aircraft noise exposure across the six months with the highest air traffic of the year ($L_{Aeq,AC,6m}$) ranged from 50 to 55 dB. Long-term exposure values were extracted from a noise contour map provided by the airport. Although the averaged noise exposure across six months did not vary considerably between the study sites, the actually measured exposure during the examination period showed high variations between the sites mainly because of the current operation direction at the airport. The equivalent sound pressure level due to aircraft fly-overs across one hour ($L_{Aeq,AC}$) ranged from 33 to 66 dB ($M = 51$ dB, $SD = 5$ dB).

2.3. Acoustical measurements

The continuous recording of the sound pressure level across four days and nights was performed by a Class-1 sound level meter (Norsonic Nor 140) and an outdoor microphone installed in a free-field position, i.e., four meters above the ground and at a minimum of five meters away from reflecting vertical surfaces. In order to respect participants' privacy, only sound pressure levels but no sounds were recorded. The sound pressure level was logged with an *A*-weighting and a *slow*-response (L_{AS}) in the interval of one second. To facilitate a post-hoc estimation of indoor levels on the basis of outdoor recordings, we performed simultaneous measurements of the outdoor and indoor sound pressure levels to derive the sound attenuation. This attenuation measurement was conducted for all typical window positions in the two rooms the participant usually spent most of the time per day (usually the living room or the home office as well as the bedroom).

For every participant and for every hour during the day, 26 noise metrics for the outdoor exposure were computed. In addition, by means of the information about the participant's whereabouts and the window position which was reported during the hourly annoyance survey, six individualized noise metrics were derived that took into account a potential outdoor to indoor attenuation of the aircraft noise level. We used these computed adjusted metrics instead of noise metrics actually measured inside the house because of the high (man-made) non-aircraft noise having the potential to mask the fly-over sounds completely. All noise metrics refer to the hour prior to the time of the annoyance assessment. For instance, when the respondent rated annoyance at 10:05 a.m., the reference period for the acoustical calculations was 9:05 a.m. to 10:04 a.m. Table 1 lists and shortly outlines the noise metrics that were obtained.

2.4. Survey instruments

Short-term annoyance during the preceding hour was rated on a semantic five-point scale (1 = not at all annoyed to 5 = extremely annoyed) following the recommendation of the International Commission on Biological Effects of Noise (Fields et al., 2001). In addition, the respondents characterized the context of the noise situation in terms of the recent whereabouts (indoors vs. outdoors or away from the area) and, if necessary, the position of the windows (closed, partially open, wide open) as well as the activity carried out in the past hour. They could choose between eight activity categories defined in the style of the categories used by Felscher-Suhr et al. (1996) which were a) *conversation* including telephoning, b) *watching TV/listening to the radio*, c) *mental work* including concentrating, reading, working at the computer, d) *physical activity* including homework, gardening, and sports, e) *leisure activities*, for instance, painting, playing an instrument,

Table 1
Outdoor and individualized noise metrics and their effect on one-hour aircraft noise annoyance. Results are from separate Generalized Estimating Equations (GEE) analyses, $N = 2678$.

Parameter	Description	*B*	*SE*	*p*	*QIC*
Number of aircraft (N_{AC}) and number of aircraft fly-overs above threshold (NAT_{xx}), respectively					
N_{AC}	No. of aircraft in total.	0.053	0.007	<.001	2229
NAT_{55}	No. of fly-overs with a maximum level >55 dB per hour.	0.054	0.007	<.001	2225
NAT_{60}	… >60 dB per hour.	0.059	0.008	<.001	2216
NAT_{65}	… >65 dB per hour.	0.066	0.009	<.001	2199
NAT_{70}	… >70 dB per hour.	0.086	0.015	<.001	2232
NAT_{75}	… >75 dB per hour.	0.103	0.034	.003	2346
NAT_{80}	… >80 dB per hour.	0.186	0.070	.008	2345
NAT_{85}	… >85 dB per hour.	0.279	0.228	.220	2352
Time with and without aircraft noise					
Total AC time [min]	Overall time in minutes influenced by aircraft noise.	0.041	0.006	<.001	2270
mean AC times [s]	Mean duration of fly-over events in seconds.	0.000	0.002	.871	2357
max no AC time [min]	Maximum unintermitted time with no fly-over sound per hour.	−0.011	0.002	<.001	2289
mean no AC time [min]	Mean unintermitted time between two fly-overs.	−0.025	0.003	<.001	2252
Energy equivalent sound pressure levels (L_{Aeq})					
$L_{Aeq,total}$	*A*-weighted energy equivalent sound pressure level (L_{Aeq}) considering both aircraft and background noise in dB.	0.052	0.009	<.001	2273
$i\ L_{Aeq,total}$*	Individualized $L_{Aeq,total}$ in dB.	0.025	0.003	<.001	2163
$L_{Aeq,bkgd}$	L_{Aeq} for background (bkgd) noise of the whole hour in dB.	0.007	0.009	.438	2359
$L_{Aeq,AC}$	L_{Aeq} exclusively for aircraft (AC) noise of the whole hour in dB.	0.047	0.006	<.001	2227
$i\ L_{Aeq,AC}$*	Individualized $L_{Aeq,AC}$ in dB.	0.026	0.003	<.001	2125
Maximum sound pressure levels (L_{Amax}) and statistical metrics (L_X)					
L_1	Sound pressure level in dB which is exceeded in 1% of the time.	0.045	0.008	<.001	2256
$i\ L_1$*	Individualized L_1 in dB.	0.025	0.003	<.001	2147
$L_{0.1}$	Sound pressure level in dB which is exceeded in 0.1% of the time.	0.027	0.006	<.001	2307
$i\ L_{0.1}$*	Individualized $L_{0.1}$ in dB.	0.023	0.003	<.001	2175
$max\ L_{Amax,AC}$	Maximum level for aircraft noise in dB across one hour (=maximum of the L_{Amax} of all fly-overs).	0.027	0.006	<.001	2302
$i\ max\ L_{Amax,AC}$*	Individualized $max\ L_{Amax,AC}$ in dB.	0.023	0.002	<.001	2169
$mean\ L_{Amax,AC}$	For each individual fly-over per hour, the L_{Amax} value in dB is computed. This parameter is the mean value from them.	0.026	0.008	.002	2330
$i\ mean\ L_{Amax,AC}$*	Individualized $mean\ L_{Amax,AC}$ in dB.	0.022	0.003	<.001	2194
(Maximum) Aircraft to background noise ratio (*SNR* and *MNR*)					
SNR	Signal to Noise Ratio (SNR) across one hour, with $L_{Aeq,AC}$ defined as “signal” and $L_{Aeq,bkgd}$ is defined as “noise”.	0.032	0.006	<.001	2299
max SNR	For each individual fly-over per hour, the *SNR* value (aircraft- vs. background noise) is computed. The *max SNR* parameter is the maximum value from them.	0.021	0.006	<.001	2339
mean SNR	The same as before, but the *mean SNR* parameter is the mean value across all individual *SNR* values.	0.014	0.008	.085	2353
max MNR	For each individual fly-over per hour the *MNR* value (maximum level of the aircraft noise vs. background noise) is computed. The *max MNR* parameter is the maximum value from them.	0.018	0.005	<.001	2338
mean MNR	The same as before, but the *mean MNR* parameter is the mean value across all individual *MNR* values.	0.012	0.007	.100	2354
Slope of rise					
max rise	Maximum of the rise time speed in dB/s of all fly-overs.	0.318	0.093	<.001	2334
mean rise	Mean of the rise time speed in dB/s of all fly-overs.	0.140	0.141	.320	2352

* Individualized aircraft noise metric. “Individualized” indicates that this metric considers the outdoor-to-indoor attenuation according to the participant's whereabouts.

and tinkering, f) *relaxation*, g) *socializing* with friends and family, and h) *eating* plus the open category i) *others*. Multiple choices were possible. The date and time of day were saved automatically. Participants filled in the questionnaire by means of survey software running on a netbook (DELL, Inspiron Mini 10) and without an experimenter being present. They were reminded of the hourly rating task by a signal tone from the netbook.

Information on personal factors was obtained in a face-to-face interview prior to and after the end of all short-term annoyance ratings. In order to facilitate a direct comparison of the impact of several personal factors on short-term versus long-term annoyance judgments, those personal and time-invariant variables were considered which were found to be significant predictors of long-term annoyance assessed by the ICBEN-scale in a recent telephone survey likewise conducted at Cologne/Bonn Airport (Bartels et al., 2013). Besides demographical data, the questions referred to the participant's general sensitivity to noise (NoiSeQ-R; Griefahn et al., 2007), the satisfaction with residential area (1 = not at all satisfied–5 = extremely satisfied), negative aspects of the local airport and air traffic (0 = none, 1 = concrete aspects mentioned), and the general attitude towards the airport of Cologne/Bonn (1 = very negative–5 = very positive). Moreover, individual measures to cope with the aircraft noise (0 = none, 1 = concrete measures mentioned) were surveyed. An additional question ascertained the respondent's environmental conscience. This variable was operationalized as the question which aspects authorities should give priority to in aviation-related decision-making (1 = environmental aspects, 2 = economical aspects, 3 = both in equal shares). Furthermore, respondents were asked about suggestions for airport actions to improve the residents' situation (0 = none, 1 = concrete actions mentioned) as well as the presence of domestic noise insulation and their satisfaction with it. For the latter, the answers of originally two questions were combined: firstly, whether domestic noise insulation has been fitted (yes or no) and secondly, in case insulation has been fitted, how satisfied the respondent is with it (1 = not at all satisfied–5 = extremely satisfied). The answers of the two questions were integrated into one variable as followed: 0 = insulation has not been fitted, 1 = insulation available but not highly satisfied with it (i.e., the individual indicated to be not at all, slightly or moderately satisfied with the insulation measures), and 2 = highly satisfied with the noise insulation (i.e., the individual indicated to be very or extremely satisfied with the insulation measures). The categorization of highly satisfied and not highly satisfied was conducted in the style of the categorization of highly annoyed persons recommended by Fields et al. (2001).

2.5. Statistical analysis

For the systematical analysis of the contribution of acoustical and non-acoustical variables to short-term aircraft noise annoyance, Generalized Estimating Equations (GEE) for linear models (Liang & Zeger, 1986; Zeger & Liang, 1986) with the working correlation matrix *AR(1)* were applied. The GEE approach was chosen as it makes no assumption about the normality of residuals and since the short-term annoyance ratings were not distributed normally (Kolmogorov–Smirnov $z = 15.11$, $p < .001$, cf. also Fig. 1). The within-subject variables were *study day* and *time of day*. To avoid problems with multi-collinearity, for each predictor class, a separate analysis was performed firstly as the acoustical parameters in particular were assumed to be highly correlated. In the second step, those acoustical and non-acoustical variables contributing significantly to annoyance were combined in a more complex prediction model. With exception for the estimation of the proportion of explained variance that was conducted manually according to the equation suggested by Zheng (2000), all statistical analyses were carried out using IBM SPSS 20.

3. Results

3.1. Descriptive statistics of annoyance ratings

Short-term annoyance responses varied between 1 and 5. As Fig. 1 demonstrates, among the total of 2719 annoyance ratings that were available for the statistical analyses, the response options 4 (very annoyed) and 5 (extremely annoyed) were chosen rarely ($n = 162$ and $n = 10$, respectively). In general, the annoyance ratings within one individual varied only slightly across the different noise situations. Across the four examination days, the standard deviations within the respondents ranged from 0.00 to 1.19 ($M = 0.70$). The mean short-term annoyance ratings across the four days ranged from 1.00 to 2.89 within the respondents ($M = 1.78$ $SD = 0.53$).

3.2. The prediction of annoyance by noise metrics

We examined the contribution of the 32 noise metrics to the one-hour annoyance rating separately for each metric. Table 1 depicts the results. The *QIC*, an adaption of the Akaike Information Criterion, *AIC*, for Generalized Estimating Equations (Pan, 2001) was used as criterion for the model fit. The lower this score, the better the fit. Since the GEE analyses were calculated only for the purpose of pre-selection, intercepts are not presented. We used only 2678 of the full sample of 2719 examination periods as no valid slope of rise could be extracted for 41 periods. The sample size needed to be identical for the comparison of the *QIC* because of its effect on the latter. Pearson's correlation coefficient between the different acoustical parameters ranged from $r = .01$ (between NAT_{85} and $L_{Aeq,bkgd}$) to $r = .99$ (between N_{AC} and NAT_{55}). Particularly high correlations were found between the $L_{Aeq,AC}$ and the number of aircraft noise events in total (N_{AC}), the number of aircraft noise events above the thresholds 55 to 70 dB(A) (NAT_{55} to NAT_{70}), statistical and maximum levels L_1, $L_{0.1}$, $max\ L_{Amax,AC}$, $mean\ L_{Amax,AC}$, and the Signal to Noise Ratio (*SNR*). All those coefficients were $r \geq .50$. The entire correlation matrix for the 32 noise metrics is published as supplementary file alongside the electronic version of this article.

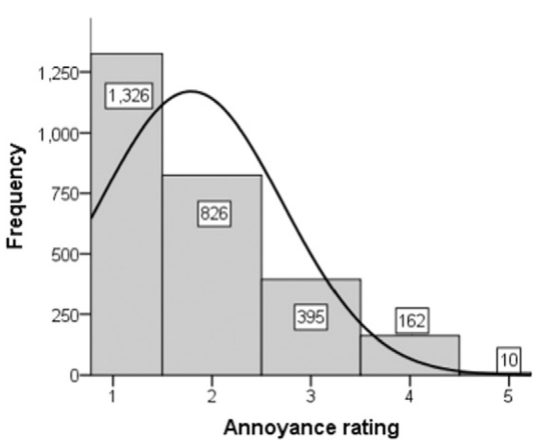

Fig. 1. Distribution of one-hour aircraft noise annoyance ratings compared to the normal curve (solid line). 1 = "not at all", 2 = "slightly", 3 = "moderately", 4 = "very", and 5 = "extremely" bothered, disturbed or annoyed, $N = 2719$.

The *outdoor* noise metric showing the lowest *QIC*-score and, hence, predicting one-hour aircraft noise annoyance best was the number of aircraft fly-overs with a peak level above 65 dB(A), the NAT_{65}. The contribution of this parameter to annoyance ratings was greater than the contribution of the more common metrics N_{AC}, NAT_{70}, $L_{Aeq,AC}$, and the maximum aircraft noise level ($max\ L_{Amax,AC}$). In total, however, individualized noise metrics showed a better model fit than parameters describing only the outdoor noise exposure. For instance, the individualized equivalent sound pressure level for aircraft noise ($i\ L_{Aeq,AC}$) accounted for 9.3% of the variance in the annoyance ratings while the outdoor equivalent sound pressure level for aircraft noise ($L_{Aeq,AC}$) explained only 6.2% of the variance. According to the *QIC*, the $i\ L_{Aeq,AC}$ was the best single predictor for one-hour annoyance ratings in total. In an iterative process, we analyzed whether stepwise introduction of additional predictors besides the $i\ L_{Aeq,AC}$ improved the *QIC*-values. As a second and third predictor we selected those variables producing the largest reduction in *QIC* following the conventions postulated by Burnham and Anderson (2004). After the third predictor no significant improvement to the model fit could be achieved by adding further predictors. This iterative process resulted in the *acoustical* prediction model presented in Table 2 that consists of the $i\ L_{Aeq,AC}$, the N_{AC}, and the NAT_{70}. These three noise parameters together explained 13.7% of the variance in the annoyance ratings and were selected for the more complex annoyance prediction model described in Section 3.5 that considered also non-acoustical factors.

3.3. The prediction of annoyance by situational factors

3.3.1. The effect of the time of day and day of the week

The presumed predictor *time of day* was operationalized as categorical variable with 17 categories corresponding to the time periods from 07:00 to 24:00. Fig. 2 depicts the estimated model-based marginal mean values of rated annoyance during the preceding hour with the effect of the acoustical parameter $i\ L_{Aeq,AC}$ controlled for. Mean ratings varied only slightly during daytime around a score of 2 (i.e., slightly annoyed). Nevertheless, in a GEE model that also included the $i\ L_{Aeq,AC}$ as a predictor, *time of day* significantly influenced the short-term annoyance rating, Wald-χ^2 (16, $N = 2719$) = 34.91, $p = .004$.

In order to simplify the model and, thus, the interpretation, the 17 time periods were combined into the four categories *morning* = 07:00–11:00, *noon* = 11:00–15:00, *afternoon and early evening* = 15:00–19:00, and *evening* = 19:00–24:00 (see Fig. 2). This variable likewise had a significant impact on one-hour annoyance ratings (Wald-χ^2 (3, $N = 2719$) = 13.79, $p = .003$). The estimated marginal means for one-hour annoyance differed slightly but significantly between the categories *noon* and *morning* ($p < .001$) as well as between *noon* and *afternoon and early evening*, and *noon* and *evening* ($p = .048$ and $p = .046$, respectively) assessed via pairwise contrast comparisons.

Table 2
GEE analysis to test the contribution of a combination of three noise metrics to short-term annoyance ratings, $N = 2719$.

Predictor	*B*	*SE*	*p*
Intercept	0.886	0.087	<.001
$i\ L_{Aeq,AC}$	0.020	0.002	<.001
N_{AC}	0.028	0.007	<.001
NAT_{70}	0.034	0.016	.029

Note. Annoyance was assessed by the question "Thinking about the past hour, how much did aircraft noise as a whole bother, disturb or annoy you?" 1 = "not at all"–5 = "extremely".

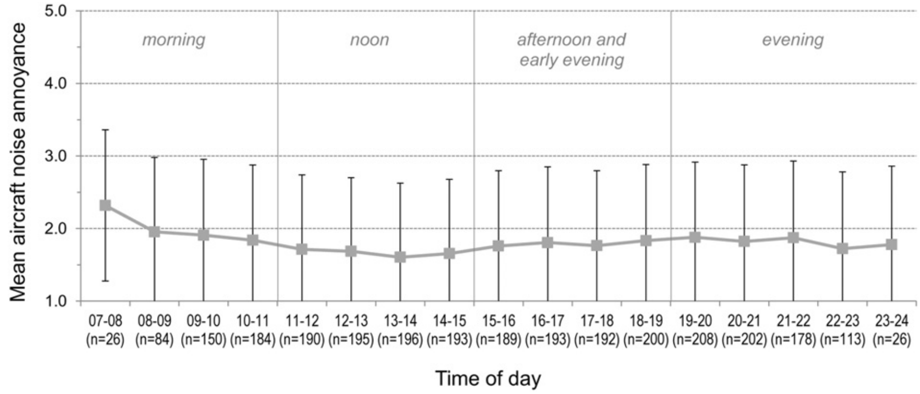

Fig. 2. Estimated marginal mean ratings (with standard errors) for one-hour aircraft noise annoyance for 17 examination periods during the day. Estimated marginal means were controlled for the effect of $i\ L_{Aeq,AC}$ with $i\ L_{Aeq,AC}$ set to the arithmetic mean (32.35 dB). One-hour annoyance was assessed by "Thinking about the past hour, how much did aircraft noise as a whole bother, disturb or annoy you?" 1 = "not at all"–5 = "extremely". Mean annoyance ratings are reported only for time periods with a sample size of $n \geq 10$. $N = 2719$.

An additional GEE analysis investigated potential differences in the annoyance ratings on weekdays and weekends. When the $i\ L_{Aeq,AC}$ was considered in the prediction model, no significant effect for the predictor *day of the week* was found (Wald-χ^2 (1, $N = 2719$) = 1.59, $p = .207$).

3.3.2. The effect of the activity

We analyzed whether noise annoyance was rated differently depending on the activity that was carried out by the respondent. Some activities are typically performed inside the house as, for instance, personal care or listening to the radio and watching TV. When the effect of the $i\ L_{Aeq,AC}$ was controlled for, annoyance was higher during *watching TV/listening to radio*, *relaxation*, and *eating* (cf. Table 3). Aircraft noise occurring during *physical activities* was perceived as less annoying (cf. Table 3).

3.4. The prediction of annoyance by personal variables

We tested whether personal and time-invariant factors such as personality traits and attitudes contributed to short-term annoyance. The following eight variables were tested in a joint GEE analysis: a) the belief that the airport could take actions to improve the residents' situation, b) the *judgment of negative aspects of the local air traffic*, c) the *attitude towards the airport*, d) the *presence and evaluation of domestic noise insulation*, e) the *application of coping measures*, f) the *satisfaction with the residential area*, g) the *environmental conscience*, and h) the respondent's general *sensitivity to noise*.[1] Only the variables *presence and evaluation of domestic noise insulation* (Wald-χ^2 (2, $N = 2719$) = 12.753, $p = .002$) and *noise sensitivity* (Wald-χ^2 (1, $N = 2719$) = 6.342, $p = .012$) affected one-hour annoyance ratings. There was no significant difference in annoyance between individuals who were highly satisfied with the noise insulation of their homes and individuals without noise insulation fitted to their homes ($B = -.174$, $SE = .124$, $p = .161$). But individuals who were not highly satisfied with the domestic noise insulation were more annoyed than those who were highly satisfied with the insulation ($B = .330$, $SE = .161$, $p = .040$). The higher respondents rated their general sensitivity to noise the more annoyed they were ($B = .269$, $SE = .107$, $p = .012$).

Table 3
GEE analysis to test the contribution of various activities on aircraft noise annoyance in the preceding hour, $N = 2719$.

Variable	*B*	*SE*	*p*
Intercept	0.851	0.090	<.001
Conversation	0.036	0.049	.464
TV/radio	0.183	0.053	<.001
Mental work	0.093	0.053	.080
Physical activity	−0.160	0.051	.002
Leisure activity	−0.008	0.089	.928
Relaxation	0.336	0.066	<.001
Socializing	−0.030	0.055	.590
Eating	0.142	0.046	.002
Personal care	0.186	0.143	.194
$i\ L_{Aeq,AC}$	0.026	0.003	<.001

Note. Annoyance was assessed by the question "Thinking about the past hour, how much did aircraft noise as a whole bother, disturb or annoy you?" 1 = "not at all"–5 = "extremely". A positive regression coefficient (B) means that annoyance was rated higher when this activity was carried out than when the other activities were carried out. A negative B indicates lower annoyance when this activity was carried out.

3.5. A combined model: predicting short-term annoyance by acoustical, situational, and personal variables

Those variables shown to significantly influence annoyance in the preceding analyses were combined in a more complex GEE model as presented in Table 4. The direction of effect of all variables remained the same as in the prior models (cf. Section 3.1 to 3.4). Only the main effect of the variable *time of day* was no longer significant at a 5% level now (Wald-χ^2 (3, $N = 2566$) = 6.834, $p = .077$). The combined model accounted for 27.6% of the variance in the annoyance judgments.

4. Discussion

4.1. The effect of acoustical parameters

Out of the 32 noise metrics assessed, the number of aircraft fly-overs with a peak level above 65 dB(A), the NAT_{65}, had the highest predictive power for one-hour annoyance. According to the *QIC*, besides the NAT_{65}, the total number of aircraft fly-overs (N_{AC}), and the number of aircraft fly-overs with a peak level above the thresholds 55 and 60 dB(A) (NAT_{55} and NAT_{60}) are better or equipollent predictors compared to the equivalent sound pressure level of aircraft noise ($L_{Aeq,AC.}$). This finding stresses the impact of noise metrics based on the number of aircraft fly-overs, the NAT_{xx} metrics, in comparison to the $L_{Aeq,AC}$ and questions the equivalent sound pressure level as best predictor of annoyance ratings. This has already been emphasized by Björkman et al. (1992) and Kastka (1999) although it is not completely clear whether results for one-hour annoyance are comparable to findings from annoyance surveys asking respondents to integrate their exposure and annoyance

[1] The variable *presence and evaluation of domestic noise insulation* is not a mere personal variable as, for instance, *noise sensitivity*. Instead, it includes information about an objective environmental state, i.e., whether noise insulation has been fitted or not. Nevertheless, it is listed under personal variables because it also comprises a subjective evaluation.

Table 4
GEE analysis testing the contribution of acoustical and situational as well as personal factors on aircraft noise annoyance in the preceding hour. $N = 2566$.

Variable	B	SE	p
Intercept	−0.217	0.309	.482
$i\ L_{Aeq,AC}$	0.020	0.002	<.001
N_{AC}	0.025	0.006	<.001
NAT_{70}	0.044	0.014	.002
Time of day			
Morning	0.109	0.066	.097
Noon	−0.043	0.052	.411
Afternoon and early evening	−0.007	0.039	.862
Evening	0[a]		
TV/radio	0.154	0.043	<.001
Physical activity	−0.194	0.046	<.001
Relaxation	0.320	0.062	<.001
Eating	0.101	0.041	.013
Presence of/Satisfaction with noise insulation			
No insulation	−0.063	0.124	.611
Not highly satisfied	0.378	0.156	.015
Highly satisfied	0[a]		
Noise sensitivity	0.292	0.095	.002

[a] This coefficient is set to 0, because the parameter is redundant as this factor level works as reference. Annoyance was assessed by the question "Thinking about the past hour, how much did aircraft noise as a whole bother, disturb or annoy you?" 1 = "not at all"–5 = "extremely".

over a considerable longer time. In a recent study examining one-hour annoyance, Schreckenberg and Meis (2006) found almost equal exposure-response correlations for the $L_{Aeq,AC}$ and the NAT_{55} ($r = .40$ and $r = .39$, respectively). For the morning hours between 07:00 and 08:00 as well in the evening between 21:00 and 22:00, the NAT_{55} even was a better predictor of annoyance than the $L_{Aeq,AC}$.

In the present field study, the number of very loud fly-overs (NAT_{80} to NAT_{85}) had no or only little impact on annoyance ratings. An explanation might lie in the relatively small number of very loud aircraft noise events during daytime. The number of fly-overs above a threshold of 80 dB(A) per hour was below 0.1 on average and never higher than 3. Obviously such a small number does not carry much weight for the annoyance assessments. Similarly, both statistical outdoor metrics indicating very high sound pressure levels in general (L_1, $L_{0.1}$) and maximum aircraft sound pressure levels outdoors ($max\ L_{Amax,AC}$, $mean\ L_{Amax,AC}$) produced a lesser model fit in terms of the QIC than the $L_{Aeq,AC}$ or metrics of the total number of fly-overs (N_{AC}) or the number of soft to moderately loud fly-overs (NAT_{55} to NAT_{70}). According to Rylander and Björkman (1997), the impact of the maximum sound pressure level depends on the number of aircraft operated at an airport: Maximum sound pressure levels are less important when the number of events is low. As breakpoint, the authors suggest 70 events per 24 h. Although the number of flights operated over the examination areas near Cologne/Bonn Airport usually is higher than 70, compared to other major European airports like Heathrow or Frankfurt the flight density is low. Hence, in conclusion, it is questionable whether the breakpoint of 70 events is still valid for current airport scenarios, since the air traffic as well as the sound pressure level per aircraft has changed significantly during the past decades (Dobrzynski, 2010; Neise & Enghardt, 2003; Quehl & Basner, 2006).

The present results indicate that individualized noise metrics predict one-hour annoyance ratings more precisely than do mere outdoor metrics. This finding has important implications for the design of future field studies on the impact of air traffic on residents' annoyance. Moreover, it stresses the relevance of situational factors given that noise exposure was determined to a major extent by the whereabouts of an individual in and around the home. The result implies that expanding subsidized noise insulation to rooms other than the bedroom – in Germany noise insulation for homes is currently granted for the bedroom only – would provide residents more opportunities to retreat from aircraft noise exposure and thereby carry out daytime activities in their homes (e.g., communication, concentrating, and recreation) undisturbed. However, the expansion and improvement of noise insulation measures must not be seen as a substitution for the attempt to reduce the outdoor exposure by operational and technological approaches. In contrary, the minimization of the outdoor exposure of aircraft noise should be given priority and only be completed by better domestic noise insulation.

Still, the proportion of variance explained by acoustical parameters (13.7%) remains surprisingly small. In comparison, for annoyance ratings referring to longer periods, such as 12 months, a rule of thumb suggests that acoustics account for approximately one third of the variance (Guski, 1999). The proportion of explained variance in short-term annoyance ratings seems particularly low if one assumes that the rater has a better memory of the exposure over the past hour than over the past year. Notwithstanding, it may also be possible that the short-term annoyance judgment reflects the exposure during other previous periods, e.g., the preceding two, three, or more hours. Furthermore, it is imaginable that the judgment refers to extremes, i.e., very low or very high exposure times. For instance, a judgment given in the afternoon might rather reflect the busy and, hence, noisy hours in the morning. Testing these hypotheses requires a methodological and statistical approach different from the one presented in this manuscript and could be part of future research. Besides, the present findings suggest a high impact of non-acoustical variables on short-term annoyance. According to the rather small variations in the annoyance ratings within one individual, it seems as if most of the respondents had a relatively stable "conviction" about how much they are annoyed by the aircraft noise in general. This conviction seems little affected by the number of fly-overs or the equivalent sound pressure level.

4.2. The effect of situational factors

4.2.1. The time of day and day of the week

The effect of the time of day found in the field study was statistically significant but rather small. When the effect of the individualized aircraft noise exposure level was controlled for, annoyance was lowest shortly after noon (13:00–14:00) and highest in the morning (07:00–08:00), which is generally consistent with the presence of a diurnal rhythm in the sensitivity to noise (Hoeger, 2004), but is in contrast to the observation of particularly high levels of annoyance in the evening and at night time (Hoeger, 2004; Hoeger et al., 2002). The results of the present field study rather support the finding of Stearns et al. (1983) and Schreckenberg and Meis (2006) who showed a significant but small increase of annoyance ratings in the evening and early morning.

According to the present results, the day of the week (i.e., weekday vs. weekends) did not affect aircraft noise annoyance, thus contrasting with earlier findings on short-term annoyance in the field (Schreckenberg & Meis, 2006). Nevertheless, both the effect of time of day and the effect of day of the week may have been underestimated for two reasons. Firstly, short-term annoyance due to aircraft noise was assessed only during the participant's waking day, i.e., when he or she was awake. Short-term annoyance was not assessed during the night, i.e., when the participant intended to sleep. At least for individuals not working night shifts, it is the night sleep that is assumed to be particularly susceptible to disturbance by noise (e.g., Basner et al., 2008; Griefahn, 2000; Porter et al., 2000). Secondly, with regard to annoyance ratings in the evening, results might have been slightly underestimated due to the examination protocol. By requesting the participants to stay at home and not go to work for four days, a kind of artificial weekend might have been created. Hoeger (2004) as well as Porter et al. (2000) concluded that individuals expect their homes to be quiet and restful and a place for recreation especially after a busy working day. During the field study days, the participants were not able to carry out their usual occupational work (except for the few self-employed). Hence, at least for those participants who did not work at home from a home office, their noise-sensitive recreational activities including leisure activities and sleep were not restricted to the time after work which is the evening hours and the weekend.

4.2.2. The activity carried out

Aircraft noise-induced annoyance rated over a period of one hour depended on the activity performed in the past hour and potentially disturbed by the noise. However, the lack of a significant effect of conversation disturbance on annoyance contradicts prior research and expectations given that a causal relationship between communication or speech interference and annoyance has been postulated by several authors in the past (Guski, 1991; Taylor, 1984; Hall et al., 1985). This lack of effect may have been due to the relatively small number of very loud fly-overs in the vicinity of Cologne/Bonn Airport. Heavy and loud (cargo) aircraft are operated in particular during the late evening and night. Hence, the maximum levels at daytime might be too low to massively disturb or interrupt active communication especially inside the house. Notwithstanding, the fact that aircraft noise is more annoying when listening to the radio or watching TV than when communicating to another person is not implausible after all. When a very noisy aircraft fly-over interferes with the conversation between human individuals so that the listener has missed important information, he or she has the chance to ask for the repetition of what was said. Simultaneously, the speaker can adjust the speaking volume. In contrast, an immediate repetition of radio or TV content is not possible and information therefore lost (Kloepfer et al., 2006). Moreover, the intermittent nature of aircraft noise exposure would necessitate repetitive and frequent adjustment of the volume, which was previously reported to cause higher disturbance ratings for aircraft noise compared to the rather continuous road traffic noise (Felscher-Suhr et al., 1996).

The finding that noise exposure during partaking of a meal was rated as more annoying was somewhat surprising as the activity eating in the nearer sense has not been regarded as particularly susceptible to interference by noise. However, in their short-term annoyance examinations, Schreckenberg and Meis (2006) have already found enhanced disturbance ratings for the activity eating. This leads to the conclusion that it is the context which is particularly susceptible to a disturbance by noise: Possibly eating is considered as a kind of social event that also offers possibilities to relax and respondents have the (implicit) expectation to be able to eat in a quiet and peaceful atmosphere.

4.3. The effect of personal factors

Although personal factors are rather time-invariant and therefore cannot account for variations within the ratings made by one individual, we expected that they lead to a general shift of all short-term annoyance ratings made by this individual towards a lower or a higher score. Therefore, the consideration of these factors seemed relevant for the explanation of variance in annoyance ratings. Among the personal factors, only *noise sensitivity* and the *presence and evaluation of domestic noise insulation* had an effect on annoyance. The former is consistent with previous studies on both long-term (Job, 1988; Miedema & Vos, 2003) and short-term annoyance (Öhrstrom et al., 1988; Schreckenberg & Schuemer, 2010). Moreover, the positive effect of a high satisfaction with domestic noise insulation measures which was found for long-term annoyance due to aircraft noise (Kastka, 1999) seems to be valid also for short-term annoyance. But at the same time, this finding suggests that a large part of personal factors, above all, attitudes, evaluations, and concerns do not play an important role for the judgment of aircraft noise-induced annoyance during short periods. This finding contradicts the results of previous laboratory studies showing a significant influence of attitudes on the annoyance rating (Djokvucic et al., 2004; Öhrstrom et al., 1988). Anyhow, it is not clear whether these findings apply to the natural living environment as well. Another study on short-term noise annoyance which was conducted at the participants' homes indeed showed that attitudes and concerns (operationalized as fears concerning the air traffic and confidence in noise authorities) had at best a small effect on one-hour annoyance ratings (Schreckenberg & Schuemer, 2010).

4.4. A combined model for the prediction of short-term annoyance

The model comprising the acoustical parameters *i* $L_{Aeq,AC}$, N_{AC}, NAT_{70}, and the situational factors *type of activity* and *time of day* as well as the person-related and rather time-invariant variables *noise sensitivity* and *presence and evaluation of domestic noise insulation* constituted the final prediction model of short-term annoyance due to aircraft noise over a period of one hour. Compared to the models containing only the equivalent outdoor sound pressure level of aircraft noise ($L_{Aeq,AC.}$) and a combination of noise metrics, the proportion of variance explained by the final model has increased remarkably by approximately 21.5% and 13.9%, respectively. Still, the proportion of variance explained remained quite small (27.6%). Even though a broad range of variables was considered still some meaningful predictors have obviously been disregarded or had to be neglected due to the study procedure. The repeating hourly survey needed to be very concise and so, for instance, the current attentional state of the respondent and mental effort due to the performance of a certain activity could not be assessed. The same applies to the present mood of the respondent. Both might have guided the judgment and interpretation of the noisy event (Andringa & Lanser, 2011; Västfjäll, 2002) and should be included in future research.

In the combined model, the effect of the factor *time of day* only showed a marginal trend towards significance. Obviously, the impact of the time of day on annoyance weights less when the activity carried out by the respondent as well as personal variables, in particular, noise sensitivity are taken into account. One reason might be that some activities go along with certain times of day as already shown in prior research (Fields, 1985). Furthermore, it is imaginable that the time of day is a significant factor only for individuals who are generally highly sensitive to noise. Possibly, highly sensitive individuals feel disproportionately more disturbed and annoyed during the times of day being associated with noise-sensitive activities (e.g., recreation, watching TV/listening to the radio) than less sensitive individuals. In contrast, less sensitive individuals are expected to show generally smaller variations in their annoyance judgments over the day due to their capability to better ignore the noise. To the authors' knowledge, this question has not been addressed yet and could be the focus of future research on noise sensitivity.

5. Conclusions

Under the assumption that short-term annoyance and long-term annoyance judgments are directly related as postulated by Porter et al. (2000) and already shown by Bartels (2014) for a subsample of the study sample presented here, two main conclusions can be drawn from the results. Firstly, aircraft noise exposure should not be judged exclusively on the basis of outdoor equivalent sound pressure levels alone. Instead, noise metrics related to the number of aircraft fly-overs should be considered as well when predicting the current status of community annoyance. These findings have practical implications regarding the determination of noise abatement zones and the regulations for granting domestic noise insulation. Moreover, these findings are relevant for operational approaches to minimize community annoyance due to aircraft noise as well. With respect to the latter, the reduction of the number of fly-overs (at certain times of a day) together with the substitution of current air fleets by less noisy aircraft with higher capacities of transporting seems to be a promising strategy. Yet it is overloaded with plenty of other difficulties: Fewer but bigger aircraft would result in fewer points and times of departure and, thus, decreased flexibility constituting a major drawback for modern, mobile 24-hour societies.

Secondly, the present findings demonstrate the large contribution of non-acoustical factors to aircraft noise-induced annoyance. Whereas prior research stressed the relevance of personal and social variables like attitudes, expectations, and traits for (long-term) annoyance the present study demonstrated the considerable impact of situational factors. With exception for noise sensitivity and the presence and evaluation of the domestic noise insulation, short-term ratings were mainly influenced by factors that characterize the context of the noise situation, i.e., the time of day and the activity carried out when the noise occurred, and the whereabouts of the respondent. In contrast, attitudinal and social factors seem to play a minor role for the assessment of annoyance during short periods.

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