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The relative impact of aircraft noise and number in a full-factorial laboratory design

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Abstract

The discussion on the extension of existing airports and the construction of new ones has reached a new peak. This paper reviews the literature on the possibility of trading noise for number of aircraft operations in the context of increasing air travel. Moreover, two new laboratory studies are presented, which model two ways of immission reduction: (1) fading out old and loud aircraft at existing airports and (2) increasing the distance to new airfields.

Three take-off recordings were combined with three numbers of events (3, 9, 27) in nine 27-min exposure conditions. In experiment 1, the different noises were recorded from different aircraft types: A322 with L_{max} 81 dB(A), B737 with L_{max} 86 dB(A), and MD80 with L_{max} 91 dB(A). Experiment 2 used an MD80 take-off recorded in distances of 1000 (L_{max} 79 dB(A)) and 500 m (L_{max} 85 dB(A)) to the start path, as well as directly beneath (L_{max} 90 dB(A)). In both experiments, the 27 min of exposure with 3 loud, 9 medium, or 27 soft take-offs had the same L_{eq} of 70 dB(A) in the exposure room. Each noise–number combination was presented to 12 subjects via loudspeakers. In total, 216 exposure sessions were performed. In both experiments, analyses of variances (ANOVA) revealed the main effects of noise and interactions with number for subjective loudness and annoyance of the experimental noise. The interaction occurred because only three noise events, whether soft, medium or loud, could produce high loudness and annoyance ratings. When subjects imagined the noise being present in the living area, both noise and number had main effects in experiment 1. In experiment 2, subjective responses increased with noise only. Apart from ANOVA, the decibel-equivalent number effect k was calculated. It was expected that k would not exceed 10, which would mean the number of noise events is not considered more than the single noise level in people's responses to the overall exposure. The analysis revealed k values ranging between -5 and 7.8, confirming that the

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number variation in the reported experiments affected the responses of the subjects less than the level variation.

1. Introduction

Noise emissions from single aircraft have been considerably reduced during the last decades. On the other hand, air traffic is increasing. Authorities and aviation operators therefore raised the question, whether the promotion of low-emission aircraft can prevent a number-induced increase in annoyance (trading noise for number).

The relative impact of the average single noise level L and the number N of its average daily occurrence on annoyance (A) is often expressed as the ratio of regression coefficients B_N/B_L taken from

$$A = B_0 + B_L L + B_N \log N + B_t \log \Delta t/T.$$

Δt is the average duration of the noise event and T the overall exposure time, which is often set to 16 or 24 h. B_N and B_L are the regression coefficients, i.e. the impact of number and level of the single noise events, respectively. The number effect $k = B_N/B_L$ indicates the relative importance of number compared to level and can therefore be labelled the decibel-equivalent number effect. It equals 10 in the equal-energy indices (e.g. L_{eq}), because a tenfold increase in number corresponds to a 10 dB increase in level. From many studies, k could be quantified, varying enormously from -3.7 to 32.8, but never being statistically significant greater than 10 (Table 1 [1–13]).

The calculation of k in laboratory studies bears several problems, two major ones are:

1. The laboratory sessions are usually rather short. On the one hand, the number of events must be projected from the experimental exposure to the usual 24 h period of consideration. In contrast, field studies can average the daily number of events over months or years, thus reducing error variability. On the other hand, subjects respond to a short exposure in an unfamiliar environment. Thus, they are likely to rate annoyance either lower due to the short exposure and the difficulty to anticipate it for a residence cycle or higher due to missing adaptation.
2. In repeated measurement designs, subjects change their ratings with increasing laboratory experience. Regression coefficients for the effects of level and number have been reported to increase [11].

Despite these problems, several laboratory studies found increases in annoyance with increases in noise level as well as number of events and provided k values ranging between 7.8 and 19.3 [10–12].

Another, more direct laboratory approach to investigate whether an energy-equivalent trade-off is possible would be to compare noise conditions of equal L_{eq} but different composition. As yet, those experiments did not reveal significant systematic increases in annoyance with increasing number of aircraft operations [14–16]. In these studies, maintaining L_{eq} while increasing number

Table 1
Decibel-equivalent number effects (k) found in field and laboratory studies

Study, year of publication	Measures	k
[1] McKennell, 1963, Heathrow	PNdB	15.0
[2] MIL, 1971, Heathrow	PNdB, worst	12.0
	PNdB, total	4.0
[3] DFG, 1974, München	Ls	20.0
[4] Fields, 1984, re-analysis of:	PNdB and:	Mean: 5.0
[1] McKennell, 1963, Heathrow	Activity	23.8
[2] MIL, 1971, Heathrow	Verbal/activity	3.2/3.0
[5] McKennell, 1977, Heathrow Concord	Verbal/activity	0.7/−1.5
[6] Grandjean et al., 1973, Zürich, Genf, Basel	Numerical	8.0
[7] Connor and Patterson, 1976, Dallas	Numerical/activity	0.8/−0.4
Los Angeles	Numerical/activity	6.1/−1.2
Chicago	Numerical/activity	8.2/7.3
Denver	Numerical/activity	−3.0/−3.7
Miami	Numerical/activity	6.4/−0.3
New York	Numerical/activity	14.0/7.6
Chattanooga	Numerical/activity	10.3/−2.5
Boston	Numerical/activity	10.5/18.0
Reno	Numerical/activity	4.4/0.8
[8] Brooker et al., 1985, Gatwick, Luton, Manchester, Aberdeen	NNI, L_{eq}, and % annoyed	9.0
[9] Bullen and Hede, 1986, Sydney	EPNL and:	24.1 ± 3.7
Richmond	General reaction	32.8 ± 103.9
Adelaide	scale, containing	6.5 ± 1.5
Perth	verbal, numerical,	16.0 ± 4.0
Melbourne	activity	16.8 ± 60.7
[10] Rice, 1977a, aircraft, laboratory	Numerical	7.8
[11] Powell, 1980, aircraft, laboratory	Numerical	14.0–19.3
[12] Namba et al., 1991, aircraft, laboratory	Verbal	10.0
[13] Kalveram, 1995, Düsseldorf	Meta-analysis	16.7

required a simultaneous variation of noise level, thus confounding number with atleast one other variable. Furthermore, the range of level–number variation was small.

Improvements on these problems were made in Ref. [17], which was a preliminary laboratory study to the experiments reported here. In the full-factorial design of Ref. [17], the used number variation had main effects on annoyance and hypothetical home assessments. However, this did not outmatch the effect of the noise range and a conversion of level to number prevented an increase in laboratory annoyance and loudness up to 10 events per half hour, particularly if single events of extremely high noise level ($L_{max} = 90$ dB(A)) were avoided. Beyond 10 events per half hour, annoyance was high even when L_{max} was relatively low. This increasing impact of number beyond a certain threshold was discussed before. Rice found no number effect below 16 events per hour [18]. Others supposed annoyance to be lowest at a medium noise medium number condition [15], which met Rice's threshold closely at 18 events per hour. However, when subjects considered domestic contexts, the tolerance of number vanished [16,17]. These findings correspond to field

Table 2
Design 1—Aircraft types, L_{max}/L_{eq} and overall L_{eq}'s of noise–number combinations in dB(A)

	A322 (81.3/71.2)	B737 (86.1/75.8)	MD80 (91.0/80.8)
3 events	$L_{eq} = 60.8$	$L_{eq} = 65.3$	$L_{eq} = 70.0$
9 events	$L_{eq} = 65.4$	$L_{eq} = 70.0$	$L_{eq} = 74.5$
27 events	$L_{eq} = 70.0$	$L_{eq} = 74.6$	$L_{eq} = 79.2$

studies, which found increasing responses to numbers of aircraft noise events especially in greater distances [19].

As in Ref. [17], the following experiments used a full-factorial 3×3 design with large variations of noise (see rows of Table 2) as well as number (see columns of Table 2), which allowed the independent calculation of noise and number main effects. Moreover, potential interactions of the two factors would appear along the designs diagonals. Since the 3 loud, 9 medium, and 27 soft noise–number combinations had equal energy, the comparison of people's responses to these conditions allowed the direct conclusion whether converting noise into number was possible without increasing adverse noise effects. The same applies for 3 medium and 9 soft as well as 9 loud and 27 medium noise events. Apart from the analysis of variances (ANOVA) approach to determine main and interaction effects, the traditional way of calculating k values according to the above-mentioned formula was followed.

In order to obtain a data basis for generalisation, the noise attenuation was modelled by the two natural ways of immission reduction: new aircraft and greater distance. Experiment 1 simulated the fade-out of old and loud aircraft, which takes place at existing airports and gave the idea of trading level for number. The research question of experiment 2, whether greater distance can compensate for number increases, is more relevant for the planning of new airports.

2. Method

Düsseldorf airport served as a model for the number variation. The take-off frequencies during the 16 h operation time in Düsseldorf vary between 10 and 20 per half hour. One number condition in the experiments was chosen well below, one close to, and one well above these frequencies: 3, 9, or 27 take-offs were presented in 27 min.

Tripling the number corresponds to an increase in level of 4.8 dB. Therefore, the noise of the single events was varied up and down as close as possible to this amount.

2.1. Experiment 1

Three different jet take-offs were recorded directly under the flight path of Düsseldorf airport (Table 2). The recordings were faded out after 50 s and digitally mixed with a 1-min recording of background noise near the airport ($L_{eq} = 48$ dB(A), forest sound of rustling leaves and very distant road noise). Three, 9, and 27 copies of each jet noise were then regularly distributed over 27 min. Pauses were filled with the background noise.

Eighteen female and 18 male students volunteered for the study (age ranging from 20 to 36 years). The factor *number* was designed as a group factor. Six male and 6 female subjects were randomly allocated to each group and exposed to either 3, 9 or 27 copies of the same aircraft noise. The factor *noise* was a within-subject factor. There were three sessions for each person with constant number but different aircraft types (rows in Table 2). Subjects visited the laboratory in weekly intervals. The sequence of the three L_{max} exposures was different for each male and female subject (complete permutation), in order to distribute laboratory experience equally to all experimental conditions.

Exposure took place via loudspeakers in a moderately sound-insulated chamber ($L_{eq} = 36$ dB (A) with loudspeakers off). The laboratory was furnished with living-room items (i.e. carpet, arm chairs, sofa, etc.). However, the atmosphere was somewhat artificial since the subjects were involved in a physiological experiment, which required periodic blood pressure measurements and saliva samples, computer-aided as well as paper–pencil questioning. The procedures of the continuous monitoring of physiological and psychological data are described in the annex and physiological results were already reported [20].

2.2. Experiment 2

Distance-varied recordings could only be performed in the forests east of Düsseldorf airport and therefore required one of the rare days with easterly winds. On a line orthogonal to the start path, the microphones were moved in order to approximate the required difference of 4.8 dB(A) between the recording points. The take-off noise of an MD80 was then recorded directly under the flight path and in distances of approximately 500 and 1000 m. The experimental tapes were comprised as in experiment 1.

Eighteen female and 18 male students volunteered for the study (age ranging from 21 to 39 years). The factor number was again a group factor, the factor noise a within-subject factor (rows in Table 3). Subjects were allocated to the noise–number conditions as in experiment 1. The full-factorial design resulted in the overall L_{eq}'s displayed in Table 3. Exposure took place as in experiment 1. Within both designs, the L_{eq} values of the equal-energy conditions in the exposure room were indeed very close. Between the designs, similarity was satisfactory: 27×1000 and 3×0 m deviated 1.3 and 1.8 dB, respectively, from the corresponding noise–number combinations in experiment 1. All other deviations were below the perception threshold of 1 dB.

2.3. Subjective noise assessment

Three stages of subjective noise assessment were conducted by the subjects as dependent variables after the exposure had ended: (1) The single noise events were rated with respect to

Table 3
Design 2—L_{max}/L_{eq} and overall L_{eq}'s of the number–distance variations

	1000 m (79.4/71.0)	500 m (84.9/75.8)	0 m (90.0/80.8)
3 events	$L_{eq} = 60.7$	$L_{eq} = 64.7$	$L_{eq} = 68.2$
9 events	$L_{eq} = 64.9$	$L_{eq} = 69.2$	$L_{eq} = 73.6$
27 events	$L_{eq} = 68.7$	$L_{eq} = 73.6$	$L_{eq} = 78.8$

loudness and annoyance. (2) The total exposure was assessed regarding loudness, annoyance and interference during the experiment. (3) A hypothetical home assessment was done of the loudness, quality and domestic interference in a living area with such noise. The impact of the number of noise events was expected to increase from the rating of the single overflight to the total exposure session and the hypothetical home assessment, because subjects consider more aspects than the mere loudness.

With numeric scales subjects indicated the interference of the noise with reading as well as annoyance and loudness of the single overflight and overall annoyance during the experimental session (questions 1–4 in the annexed questionnaire). Additionally, overall loudness was rated numerically (question 5) and overall annoyance was assessed on a seven-point verbal scale (question 11). The latter was used in many German noise studies, for example Refs. [15–17,19]. Finally, subjects were asked to imagine residential areas with that noise and to rate 19 items of expected domestic interference, e.g. "one must increase the volume of radio and television" [21] as well as the quality and loudness of the living area (questions 12–14 in the annexed questionnaire). These hypothetical home assessments were performed to help the subjects anticipating long-term effects of that noise at home.

Apart from these main dependent variables, the total number of perceived noise events (question 7) as well as the number of different aircraft types (question 15) and the estimated recording distance (question 8) were obtained to control whether the variations of noise and number were perceived by the subjects. Finally, a few items of the questionnaire were not analysed, because they were redundant to the above-mentioned aspects (question 3) or of minor relevance for the research question at issue (questions 6 and 9 on valence and threat). Also question 16, which asked whether subjects would counteract the noise source, retreat or wait and see (full item list in the appendix), was ignored because it was the last in the questionnaire and many subjects were already eager to leave the laboratory.

The above-mentioned dependent variables (questionnaire items 1–4 and 11–14) were used to determine the respective decibel equivalent number effects k. The other questionnaire items were either only used as control questions (items 7, 8, and 15), not unidirectional (item 6) or not scaled (item 10), and therefore not suitable for k calculation.

2.4. Statistical analyses

ANOVA with subsequent t-tests were used for statistical testing. The main effects of noise and number were localised using row and column means, respectively. In case of significant interactions, Pillai's trace was used for estimating F-values, and equal-energy conditions were compared via t-tests. The overall assessments of loudness (question 5), annoyance (question 11), hypothetical domestic interference (question 12) and residential quality (question 13) were subjected to ANOVA. Accordingly, means and standard errors are provided for these four items in Table 4. Compared to the k value calculation, which gives the impact of the number of noise events only relative to their level, the ANOVA procedure has the advantage that single main effects of number as well as noise and their interactions are determined.

The decibel-equivalent number effect was calculated for both designs using the formula mentioned above, where A was the self-reported response according to the respective scale, L the peak noise levels in dB(A) (80, 85 and 90), and N the number of events (3, 9, 27 in 27 min) projected

Table 4
Means ± standard errors for the different noise assessment scales in experiment 1 (aircraft type variation) and experiment 2 (recording distance variation)

	A322	B737	MD80
Question 5	*Overall loudness, numeric*		
3 events	6.58 ± 0.49	5.75 ± 0.49	6.92 ± 0.54
9 events	5.67 ± 0.48	6.42 ± 0.44	5.67 ± 0.54
27 events	5.83 ± 0.60	5.50 ± 0.38	6.92 ± 0.44
Question 11	*Overall annoyance, verbal*		
3 events	4.83 ± 0.27	4.58 ± 0.31	5.42 ± 0.23
9 events	4.08 ± 0.36	5.00 ± 0.37	4.58 ± 0.29
27 events	4.50 ± 0.38	4.75 ± 0.33	5.50 ± 0.29
Question 12	*Mean expected domestic interference*		
3 events	2.77 ± 0.20	2.79 ± 0.21	3.23 ± 0.19
9 events	2.98 ± 0.22	3.29 ± 0.24	3.18 ± 0.26
27 events	3.60 ± 0.23	3.76 ± 0.20	3.78 ± 0.17
Question 13	*Quality of imagined living area*		
3 events	3.58 ± 0.23	3.75 ± 0.25	4.00 ± 0.17
9 events	3.83 ± 0.24	4.08 ± 0.23	4.00 ± 0.21
27 events	4.25 ± 0.18	4.67 ± 0.14	4.50 ± 0.15
	1000 m	500 m	0 m
Question 5	*Overall loudness, numeric*		
3 events	6.67 ± 0.36	6.25 ± 0.43	7.50 ± 0.36
9 events	5.17 ± 0.44	5.25 ± 0.55	6.67 ± 0.46
27 events	5.58 ± 0.56	6.75 ± 0.39	7.92 ± 0.15
Question 11	*Overall annoyance, verbal*		
3 events	5.17 ± 0.30	5.00 ± 0.35	5.17 ± 0.24
9 events	4.17 ± 0.34	4.17 ± 0.37	5.00 ± 0.35
27 events	4.42 ± 0.36	5.25 ± 0.28	5.92 ± 0.29
Question 12	*Mean expected domestic interference*		
3 events	3.62 ± 0.14	3.70 ± 0.12	3.64 ± 0.15
9 events	3.14 ± 0.32	3.11 ± 0.34	3.41 ± 0.30
27 events	3.06 ± 0.14	3.60 ± 0.16	3.76 ± 0.15
Question 13	*Quality of imagined living area*		
3 events	4.25 ± 0.18	4.08 ± 0.23	4.24 ± 0.22
9 events	3.75 ± 0.18	3.67 ± 0.23	4.25 ± 0.18
27 events	4.17 ± 0.21	4.33 ± 0.19	4.83 ± 0.17

to 24 h. The planned noise levels were used instead of the measured levels, because also the ANOVA used the three planned levels of the factor noise and the outcomes of both calculation methods will be compared. However, the deviations of actual from planned noise levels were small and unsystematic due to several calibration procedures before the experimental sessions.

2.5. Hypotheses

It was expected that subjective responses to the total exposure session would follow an equal-energy model. Therefore, noise ratings should increase from column to column with noise as well as with number in the rows. Equal-energy conditions (diagonals in the design) should cause equal responses. Statistically, this would be reflected by two main effects in the ANOVA.

The decibel-equivalent number effect k was calculated for each unidirectional, scaled self-reported noise effect and expected not to be significantly different from 10 (equal-energy hypothesis).

3. Results

After exposure, subjects estimated the number of aircraft overflights (question 7 in the annexed questionnaire), their distance (question 8), and the number of different aircraft types (question 15). These items served as control questions in order to check whether the independent variables number and noise, the latter varied by distance and aircraft type, were perceived by the subjects. The different number conditions were indeed discriminated; however, the number of reported overflights was consistently overestimated by about one third: 3 noise events were on average perceived as 4, 9 as 11 and 27 as 35, respectively. There were neither systematic nor significant differences between the within-subject noise level conditions or the two experiments. Subjects also overestimated the number of different aircraft types in both experiments. While they heard only one and the same noise in each session, they reported on average 1.5 different aircraft types in the 3-event condition, 2 in the 9-event condition, and 3 in the 27-event condition. However, these differences were not statistically significant. The recording distance was estimated on average between 300 and 1500 m. Subjects again regularly overestimated the distances in both experiments, apart from the 3×1000 and 9×1000 m conditions in experiment 2, in which the recording distance was rated 700 m on average and thereby smaller as it actually was. Probably due to the fact that laboratory subjects do not have enough cues to distance to make a realistic estimation, error variability was very high (the grand mean had a standard deviation of about 720 m in experiment 2). In conclusion, the control questions revealed that subjects tended to overestimate the number of noise events and aircraft types as well as the recording distance. However, in relative (not absolute) numbers, the intended independent variation of number and noise was perceived by the subjects.

As the first main dependent variable, subjects rated the loudness of explicitly the whole 27-min exposure session. Table 4 shows that subjective loudness did not systematically increase with either noise or number in experiment 1. Against the hypothesis, even the three soft take-offs of A322 caused an average loudness rating of 6.58 on a nine-point scale. Statistically, this resulted in a significant interaction ($F_{4,66} = 2.61$, $p = 0.04$; Table 5).

Table 5
Report of the analyses of variances—F(hypothesis degrees of freedom, error degrees of freedom) and p-values (in case of interactions estimation of F using Pillai's trace)

	Main effect Noise	Main effect Number	Interaction
Question 5	*Loudness*		
Aircraft type	$F(2, 66) = 2.21$	$F(2, 33) = 0.46$	$F(4, 66) = 2.61$
	$p = 0.118$	$p = 0.655$	$p = 0.043$
Distance	$F(2, 66) = 21.00$	$F(2, 33) = 3.05$	$F(4, 66) = 1.91$
	$p = 0.000$	$p = 0.061$	$p = 0.119$
Question 11	*Annoyance*		
Aircraft type	$F(2, 66) = 8.80$	$F(2, 33) = 0.64$	$F(4, 66) = 3.44$
	$p = 0.000$	$p = 0.532$	$p = 0.013$
Distance	$F(2, 66) = 11.92$	$F(2, 33) = 2.21$	$F(4, 66) = 3.56$
	$p = 0.000$	$p = 0.125$	$p = 0.011$
Question 12	*Mean expected domestic interference*		
Aircraft type	$F(2, 66) = 4.77$	$F(2, 33) = 4.31$	$F(4, 66) = 1.77$
	$p = 0.012$	$p = 0.022$	$p = 0.146$
Distance	$F(2, 66) = 7.08$	$F(2, 33) = 1.00$	$F(4, 66) = 3.15$
	$p = 0.002$	$p = 0.379$	$p = 0.023$
Question 13	*Quality of imagined living area*		
Aircraft type	$F(2, 66) = 4.12$	$F(2, 33) = 4.38$	$F(4, 66) = 0.62$
	$p = 0.021$	$p = 0.021$	$p = 0.653$
Distance	$F(2, 66) = 10.32$	$F(2, 33) = 2.70$	$F(4, 66) = 2.31$
	$p = 0.000$	$p = 0.082$	$p = 0.067$

In experiment 2, the average loudness rating increased with the level of the single events ($F_{2,66} = 21.00$, $p = 0.000$; Table 5), whereas response to number decreased from 3 to 9 events.

With respect to the mean overall annoyance resulting from each of the exposure sessions, varying aircraft type and distance resulted in significant main effects of the factor noise ($F_{2,66} = 8.80$, $p = 0.000$; $F_{2,66} = 11.92$, $p = 0.000$). However, an interaction with number was superimposed, as even 3 events caused average annoyance ratings around five on the seven-point scale ($F_{4,66} = 3.44$, $p = 0.013$; $F_{4,66} = 3.56$, $p = 0.011$). Three MD80 tended to be more annoying than 27 A322, and 3 take-offs with 0 m lateral distance caused more response than 9 in 500 m distance ($p < 0.025$, not significant with alpha correction).

The 19 domestic interference items resulted in one main component as already in the investigation of Leonard and Borsky [21]. Therefore, the ratings were averaged and only the mean expected domestic interference was related to the experimental sessions.

Tables 4 and 5 show that mean domestic interference increased with noise ($F_{2,66} = 4.77$, $p = 0.01$) and number ($F_{2,33} = 4.31$, $p = 0.02$) in experiment 1 as expected. Experiment 2 resulted in a main effect of noise ($F_{2,66} = 7.08$, $p = 0.002$) and in an interaction ($F_{4,66} = 3.15$, $p = 0.023$), which was due to the high responses in the low number sessions.

Table 6
Number effects k in the two experiments varying noise by aircraft type and distance, respectively

Number in questionnaire	Item	Decibel-equivalent number effects k			
		Aircraft	Distance	Amplification [17]	Mean
1	Interference	−5.00	7.63	0.80	1.14
2	Annoyance single event	−0.70	2.35	2.35	1.33
3	Overall annoyance, numeric scale	−0.60	2.63	0.63	0.89
4	Loudness single event	−0.20	1.33	1.33	0.82
11	Overall annoyance, verbal scale	0.14	0.39	0.80	0.44
12	Mean domestic interference	2.90	7.82	0.70	3.81
13	Quality of living area	2.60	1.18	0.35	1.38
14	Loudness of living area	3.10	1.10	0.52	1.57
	Mean	0.28	3.05	−0.5	0.37

Additionally, Ref. [17] was analysed, an experiment using nine independent groups of ten subjects and one 85 dB aircraft noise, which was attenuated and amplified by 5 dB.

The subjects imagined the living area, where the noise was recorded. Their assessments of the quality of this living area depended mainly on noise, but also on number. Noise had main effects in both experiments ($F_{2,66} = 4.12$, $p = 0.02$; $F_{2,66} = 10.32$, $p = 0.000$) and number only in experiment 1 ($F_{2,33} = 4.38$, $p = 0.02$; Tables 4 and 5). In experiment 2, the main effect of noise was localised between 0 and 500 as well as 1000 m ($t = 4.51$, $p = 0.000$; $t = 3.62$, $p = 0.001$).

The decibel-equivalent number effects k ranged between −5.0 and 7.8 (Table 6) for the two experiments with aircraft and distance, which confirms that number affected annoyance less than level. Testing the mean k value of all dependent variables in experiments 1 and 2 against the equal-energy hypothesis of $k = 10$ resulted in a significantly smaller number effect of $k = 1.7$ ($t = -10.81$, $p = 0.000$).

Table 6 also shows number effects of a similar experiment [17] varying a take-off noise with L_{max} 85 dB(A) by attenuation and amplification of 5 dB(A). The design corresponded to the designs of experiments 1 and 2, with the exception that each subject was randomly assigned to only one noise–number combination. Altogether, 90 subjects volunteered in Ref. [17] and, as mentioned above, ANOVA revealed significant main effects of number. However, this is not reflected by the k-values, which are equally low as in experiments 1 and 2.

The three different experimental designs reported here and in Ref. [17] did not produce significantly different number effects (MANOVA for the eight self-report scales of Table 6, $F_{2,6} = 1.650$; $p = 0.268$). However, trading the number for the distance of noise events in experiment 2 tended to reveal a higher k. This is in line with the result of field studies [19] that many aircraft operations cause community responses also in great distances.

4. Discussion

Regarding the mere laboratory assessment, loudness and annoyance did not systematically increase with either noise or number in experiment 1. However, with overall L_{eq} held constant, subjects tended to tolerate higher numbers. Experiments 1 and 2 revealed the clear main effects of noise within each number condition when "laboratory" annoyance was rated.

Hypothetical home assessments revealed systematic effects of noise and number in experiment 1, and of noise only in experiment 2. One possible explanation for the significant effect of number with respect to this item may be that subjects more thoroughly thought about the consequences of the noise when considering domestic contexts. Apart from greater personal involvement in general, they probably take into account longer-term exposure and non-acoustical factors like air pollution [15,16]. However, it has to be further investigated whether hypothetical home assessments can be a valid prediction of field responses.

The decibel-equivalent number effects calculated from the two experiments were significantly smaller than 10. This also indicates that laboratory annoyance did not increase with the number of noise events. The main reason for this is supposed to be an underestimation of annoyance in the short and rather artificial experimental exposure. The majority of laboratory data [10,12,17] revealed number effects of 10 or smaller. Therefore, the method of calculating k values from laboratory data might be challenged by the ANOVA approach, which seems to be more sensitive in detecting number effects and moreover can depict interactions of both factors.

Another limitation of within-subject experiments was raised by Powell [11]: In his study with five experimental sessions, the regression coefficients for both level and number increased with laboratory experience. In experiments 1 and 2, subjects were randomly assigned to a number condition and visited the laboratory three times in weekly intervals to hear either soft, medium or loud overflights. However, the sequence of level exposure was fully permuted and thus laboratory experience affected all $L_{\max}$ conditions equally. In contrast to Ref. [11] with five sessions, the ratings of the subjects in experiments 1 and 2 were influenced only by one prior visit on average. Other experiments with no repeated measurements revealed no significantly different k-values [17].

Finally, as the analyses of variances of hypothetical home assessments have shown, the number effect tended to be higher if real living areas were considered. Again, the method of k-value calculation failed to detect this.

On the basis of the ANOVA results, it is concluded that the effect of the investigated noise range was stronger than the influence of the used number variation in both reported experiments and for all self-report items. In agreement with the majority of other laboratory studies [10,12,14–17], number did not influence laboratory annoyance more than in an equal-energy model. However, the assessment of (imagined) living areas in experiment 1 depended on both the noise and number variation alike (two ANOVA main effects). Moreover, in field studies, it is assumed that the increasing number of events might outmatch level reduction and lead to even greater annoyance [19]. Therefore, a potential number effect especially in domestic contexts cannot be excluded and should be further considered using full-factorial designs.

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Appendix A. Translated and original study instructions and scales

A.1. Study instruction to the subjects

Dear participant,

Thank you very much for volunteering in this study. The experiment will last about 1 h. During this time, environmental noise will be presented to you via the loudspeakers in front of you and you will be asked to answer questions on the computer. Please answer the questions spontaneously and without musing too long! Between two questionnaires, you may read one of the Geo-magazines to the right in front of you. Please try to relax as much as possible.

The experimenter will soon mount a cuff for blood pressure monitoring. Your blood pressure will be measured in regular intervals. When you feel the cuff on your right arm inflating, relax your right arm and do not move it any more. After the cuff has deflated (after about 1 min), please go on reading or writing.

A pulse meter will be placed on the middle finger of your left hand. It is sensitive to pressure and movements. Therefore, please relax your left arm on the arm-rest of your chair and move hand and finger—also during activities of your right hand—as little as possible!

In front of you on the table is a rack with 5 tubes. In the course of the experiment, you will be asked repeatedly via an instruction on the computer screen to put some saliva from your mouth into the tube with the respective number. (Please do not try to produce more saliva than actually is in your mouth.) Please take, when instructed for the first time, tube number 1 with your right hand, spit saliva into it, and put the tube back to position 1. In case you drop a tube, please do not pick it up, but take one of the substitutes lying on the table. When the second instruction for saliva sampling appears, take tube number 2, spit saliva into it, place it back to position 2 and so forth until all tubes are used.

Please tell the experimenter now if you have questions or if you would like to cancel your participation. If not, please let him/her mount the sensors. All other instructions will be given via the computer screen to the right in front of you.

Liebe Versuchsteilnehmerin, Lieber Versuchsteilnehmer,

Vielen Dank, dass Sie sich bereiterklärt haben, an dieser Untersuchung teilzunehmen. Der Versuch dauert insgesamt etwa eine Stunde. In dieser Zeit werden Ihnen Umweltgeräusche über die vor Ihnen befindlichen Lautsprecher dargeboten und Sie werden gebeten, am Computer einige Fragebogen auszufüllen. Bitte beantworten Sie die Fragen spontan und ohne lange nachzudenken! Wenn sie gerade keine Fragebogen ausfüllen, können Sie sich eins der rechts neben Ihnen liegenden Geo-Hefte nehmen. Bitte versuchen Sie, sich so weit wie möglich zu entspannen.

Der/die Versuchsleiter/in wird Ihnen gleich eine Manschette zur Blutdruckmessung anlegen. Ihr Blutdruck wird in regelmäßigen Abständen gemessen werden. Wenn Sie spüren, dass sich die Manschette an Ihrem rechten Arm aufpumpt, strecken Sie bitte locker Ihren rechten Arm und bewegen Sie ihn dann nicht mehr. Sobald die Manschette abgepumpt ist (nach ca. einer Minute), können Sie mit Lesen oder Schreiben fortfahren.

Am Mittelfinger Ihrer linken Hand wird ein Pulsfühler angebracht. Dieser reagiert sehr empfindlich auf Druck und Bewegung. Bitte legen Sie Ihren linken Arm deshalb locker auf die Armlehne und bewegen Sie Hand und Finger—auch während der Tätigkeiten, die Sie mit Ihrer rechten Hand ausführen—so wenig wie möglich!

Vor Ihnen befindet sich auf dem Tisch ein Ständer mit 5 Plastikröhrchen. Während des Versuchs werden Sie einige Male über den Monitor aufgefordert, in das jeweilige Röhrchen den Speichel zu geben, den Sie gerade im Mund haben. (Bitte versuchen Sie nicht, mehr Speichel zu erzeugen, als sich in Ihrem Mund befindet). Bitte nehmen Sie, wenn Sie das erste Mal dazu aufgefordert werden, mit Ihrer rechten Hand das Röhrchen Nr. 1 aus dem Ständer und geben Sie den Speichel hinein, bevor Sie es wieder an Platz 1 zurückstellen. Sollte Ihnen ein Röhrchen herunterfallen, heben Sie es bitte nicht auf, sondern ersetzen es einfach durch eines der auf dem Tisch liegenden Ersatzröhrchen. Bei der zweiten Aufforderung zur Speichelgabe nehmen Sie Röhrchen Nr. 2 heraus, geben Speichel hinein, stellen es an Platz 2 zurück usw., bis alle Röhrchen verbraucht sind.

Bitte sagen Sie jetzt dem/der Versuchsleiter/in Bescheid, wenn Sie Fragen haben oder die Teilnahme am Versuch beenden möchten. Ansonsten lassen Sie ihn/sie die Geräte anlegen. Alle weiteren Instruktionen bekommen Sie über den Bildschirm rechts von Ihnen.

Translation of the noise assessment questionnaire handed in as paper copy immediately after the noise had ended

	Question	Scale	Descriptors
1.	Imagine this is a thermometer that measures the interference from noises. 10 means that the noises interfere unbearably, 0 means that the sounds do not interfere at all. How much did the aircraft noise of the past thirty minutes interfere with your reading?	11	Not at all, unbearably interfering
2.	How annoying was every single overflight?	10	Not at all, extremely annoying
3.	How annoying were the aircraft noises overall?	10	Not at all, extremely annoying
4.	How loud was every single overflight?	10	Not at all, extremely loud
5.	How loud were the aircraft noises overall?	10	Not at all, extremely loud
6.	How pleasant or unpleasant did you find the aircraft noises?	10	Very pleasant, very unpleasant
7.	How high do you estimate the number of overflights in the past 30 min?	Number	
8.	Judging from the noise, how many metres would you estimate were between you and the aircraft?	Metres	
9.	How threatening were the aircraft noises overall?	10	Not at all, extremely threatening
10.	Were the aircraft noises acceptable or unacceptable?	2	Acceptable, unacceptable

11.	How annoying were the aircraft noises overall?	7	Not at all, very weakly, weakly, clearly, highly, very highly, unbearably annoying
12.	If you were exposed to the aircraft noises of the last 30 min every day at home, how often would the following noise effects occur to you? a. One must increase volume of radio and television b. You cannot open the windows c. Interferes with television d. Causes arguments in the family e. Makes you feel tense and edgy f. Interferes with conversations to friends and acquaintances g. Spoils leisure time h. Trembling house and room walls i. Clattering windows and dishes j. You must raise your voice k. Prevents relaxation and after-work rest l. You are startled m. You get a headache n. Keeps from falling asleep o. Interferes with reading and thinking p. Wakes you up at night q. Causes ear pain and hearing problems r. You hate being outside s. Spoils the pleasure of a promenade	5	Never, seldom, some times, often, always
13.	How do you rate the quality of living in the area where the aircraft noises were recorded?	5	Very good, good, average, bad, very bad
14.	How do you rate the loudness of the area where the aircraft noises were recorded?	5	Not, little, medium, considerable, very loud
15.	How many different aircraft types did you hear in the past 30 min?	Number	
16.	If you were exposed to the aircraft noises of the last 30 min every day at home, what would you do? a. Keep windows closed b. Drown out the noise by radio or television c. Write a complaint letter or make a protest call via telephone d. Install sound insulating windows e. Move away	5	Very unlikely, unlikely, possibly, likely, very likely

f. Found a citizens committee
g. Take sleeping pills or calmative medication
h. Gather information about the noise problem
i. Use ear protection plugs or the like
j. Despite the anger wait and see
k. Try to ignore the noise
l. Resign yourself to the noise because nothing can be done
m. Adjourn to a calmer part of the flat
n. Stay home rarely
o. Balancing activities (e.g. sports)

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