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Relative duration of quiet periods between events influences noise annoyance: a laboratory experiment with helicopter sounds

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Abstract

Besides the commonly considered time-averaged noise exposure metrics such as the L_{den}, additional indicators (e.g., maximum level, eventfulness, or relative quiet time) might improve the prediction of noise annoyance. An experiment was carried out on the effects of relative duration of quiet periods on annoyance reactions to helicopter noise scenarios, with the relative duration being the ratio of total duration of quiet periods in a sound scenario to its total duration. Recorded flybys were spatially reproduced with a hemispherical loudspeaker array in the laboratory. Ninety-second noise scenarios were prepared, containing two, three, four, or five flybys. All scenarios exhibited the same L_{eq} of 66.5 dB(A), however, differed in the number of flight events and the exposure levels of individual flybys. Subjects were asked to make paired comparisons (i.e., two-alternative forced choices) for three pairs of scenarios. In each pair, one scenario had a larger number of flybys than the other; i.e., 4 vs. 2, 5 vs. 2, or 5 vs. 3. An analysis of the data of 56 subjects was carried out to investigate the effect of the relative duration of quiet periods between events on annoyance. The results indicate that longer quiet periods may mitigate noise annoyance.

Keywords: Noise annoyance, psychoacoustic laboratory experiment, quiet periods, helicopter noise

1 INTRODUCTION

To estimate noise impact such as annoyance, often time-averaged noise exposure metrics are used as predictors, such as the equivalent continuous sound pressure level (L_{eq}), day-night level (L_{dn}), and day-evening-night level (L_{den}) [1, 2, 3]. This ignores the temporal structure of the noise and other acoustical characteristics over the measurement period. Indicators such as the maximum level, source type, dominant events, relative quiet time, etc. might be additional indicators of annoyance. That is, at equal average levels, these parameters might be the differentiating factor, as to why one noise situation is more annoying to humans than the other. For example, with respect to the source type, at comparable sound pressure levels (e.g., L_{eq} or L_{den}), aircraft noise seems to be more annoying than road traffic or railway noise [3, 4, 5].

Fleischer [6, 7] suggested that, quietness should be considered in noise measurement in addition to the averaged level. Various methods of consideration of quiet periods were investigated by Finke [8], Krause [9], Guski [10, 11, 12], and by Estévez-Mauriz and Forssén [13]. On the one hand, they emphasized the need for consideration of quietness in noise measurement. On the other hand, they suggested that not only the total length of quiet periods, but also their distribution and individual durations could be important [8, 12, 13]. The hypothesis is that longer quiet periods (in total and individually) might mitigate annoyance.

Furthermore, it was suggested that it should be differentiated between absolute quiet backgrounds containing only low-level natural sounds and relative quiet backgrounds in the cities, whereby ventilation and heating devices etc. could cause a minimum background level which is higher than in the nature. Thus, it should be differentiated between quietness level in the first case and the recovery level in the latter case, respectively [6, 7, 8, 9].

Dornic and Laaksonen [14] investigated effects of intermittency (i.e., noise interruptions or calm periods) on annoyance in a laboratory experiment. Three kinds of white noise were used,: continuous, intermittent regular, and intermittent irregular. It was found that intermittency reduced the perceived annoyance. However, in contrast to other suggestions (e.g., [12, 13]) regularity or irregularity of the intermittency did not affect annoyance (in the particular case of white noise stimuli) [14].

With that background, this paper investigates the effect of quietness by means of a psychoacoustic experiment. At the same A-weighted equivalent continuous sound pressure level (L_{Aeq}), annoyance from stimuli with different numbers and lengths of quiet periods were judged in paired comparisons.

2 DIFFERENTIATING INDICATORS

A series of indicators have been used in this paper, which will be described briefly as follows.

2.1 Number of events

It has been shown that the number of noise events might be an additional predictor of annoyance [15, 16, 17]. Since in this study isolated flight events were mixed to prepare stimuli, the number of flight events in each scenario was directly available and was investigated as a possible indicator to predict annoyance.

2.2 Relative duration of quiet periods

Based on suggestions by Fleischer [6], Krause [9] delivered a formula to calculate the relative duration of quiet periods as the ratio of total duration of quiet periods to total duration of a scenario. First, the total duration of quiet periods $\mathrm{T}_{\mathrm{quiet}}$ in a scenario is calculated as

$$\mathrm{T}_{\mathrm{quiet}} = \sum t_i, \tag{1}$$

whereby t_i is the duration of the i-th (individual) quiet period in the scenario (e.g., in seconds). Then, the relative duration of quiet periods is calculated as

$$\text{Relative duration of quiet periods } (\%) = 100 \cdot \frac{\mathrm{T}_{\mathrm{quiet}}}{\mathrm{T}_{\mathrm{scenario}}}, \tag{2}$$

whereby $\mathrm{T}_{\mathrm{scenario}}$ is the total duration of a scenario (e.g., in seconds; i.e., the same unit as for t_i and $\mathrm{T}_{\mathrm{quiet}}$).

2.3 Intermittency ratio (IR)

Wunderli *et al.* [18] introduced intermittency ratio (IR) as a measure for the eventfulness and intermittency of a scenario. It considers the individual dominant events which arise from the average-level background [4, 18]. Intermittency ratio is defined as

$$IR\ (\%) = 100 \cdot 10^{0.1(L_{\mathrm{Aeq},T,\mathrm{Events}} - L_{\mathrm{Aeq}})}, \tag{3}$$

whereby $L_{\mathrm{Aeq},T,\mathrm{Events}}$ is calculated from contributions of events, the level of which exceed a given arbitrary threshold K:

$$K = L_{\mathrm{Aeq}} + C[\mathrm{dB}]. \tag{4}$$

For the calculation of K, C is the dB-offset (i.e., the dB difference to L_{Aeq}) beyond which events are considered [18]. In this paper, $C = 3$, as suggested by Wunderli *et al.* [18].

2.4 Centre of Mass Time (CMT)

Estévez-Mauriz and Forssén [13] introduced Centre of Mass Time (CMT) as an indicator for quiet periods, which penalizes the fragmentation of quieter periods and values its clustering (i.e., longer time periods). CMT (in seconds) is calculated as

$$CMT = \frac{\sum {t_i}^2}{\sum t_i}, \tag{5}$$

whereby t_i is the duration of the i-th (individual) quiet period in the scenario (in seconds).

3 METHOD

3.1 Listening test facility

The experiment was conducted in AuraLab, a listening test facility of the authors' institution Empa, which has a separate listening and control room allowing for audio-visual supervision [19, 20]. AuraLab satisfies room acoustical requirements for high-quality audio reproduction in terms of its background noise and reverberation time. A 3D immersive sound system with 16 separate audio channels was used for the present study. Fifteen loudspeakers "KH 120 A" (Georg Neumann GmbH, Berlin, Germany) were located in a hemispherical arrangement on three height levels (0, 30, and 60° elevation) in a distance of 2 m from the central listening spot. Two subwoofers "KH 805" (Georg Neumann GmbH, Berlin, Germany) and a digital signal processor (DSP) completed the playback system [19].

3.2 Stimuli

3.2.1 Recordings

The helicopter noise samples originated from field recordings (landings and takeoffs) at Grenchen Airport, Switzerland (ICAO code: LSZG) [19]. Details about the recordings can be found in [19]. The recordings selected for this experiment were from helicopter types A109, A119, AS35, and EC20, all of which are categorized as light-weight civil helicopters (weight: 1.7-3.2 tons) [19, 21].

Background ambient sounds of birds and vegetation were recorded by means of an Ambisonic microphone Soundfield SPS200 (Soundfield, London, UK) and an additional measurement microphone (to calibrate the system). The level (L_{Aeq}) of the background ambient sounds was 37.5 dB(A) [19].

3.2.2 Processing

The recorded helicopter signals underwent a series of processing steps: preprocessing, optional propagation filtering, optional (minor) level shift, spatialization, and adding background ambient sound. Details about the processing steps are given by Taghipour *et al.* [19].

3.2.3 Stimuli set

Six ninety-second scenarios (i.e., stimuli) were generated, in which two (twice), three, four, or five (twice) helicopter events were present. Each individual helicopter event lasted 16 s (including fade-in and -out ramps of 2 s, arising from and disappearing in the ambient background sound). The ninety-second stimuli were also faded in and out with 2-s ramps. Squared cosine ramps were used for all fadings. Figure 1 shows the level-time histories (L_{AF} curves) of the stimuli used for this experiment. The stimuli were played back at a sampling frequency of 48 kHz and had an L_{Aeq} of 66.5 dB(A).

The number of flight events, the absolute and relative durations of quiet periods, the IR, and the CMT are listed in Table 1 for the individual stimuli. To calculate the absolute and the relative duration of quiet periods as well as the CMT, periods without flight events (of 16 s each) were defined as "quiet." That is, the background ambient sound of 37.5 dB was considered as a "quiet" (i.e., recreational) background.

Table 1. Measures of quiet periods for the stimuli.

Scenario	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Number of events	2	2	3	4	5	5
Absolute duration of quiet periods, T_{quiet} (s)	58	58	42	26	10	10
Relative duration of quiet periods (%)	64.4	64.4	46.7	28.9	11.1	11.1
Intermittency ratio, IR (%)	85.01	84.04	70.45	52.83	33.26	26.16
Centre of Mass Time, CMT (s)	20.59	19.48	11.19	6.15	1.80	1.80

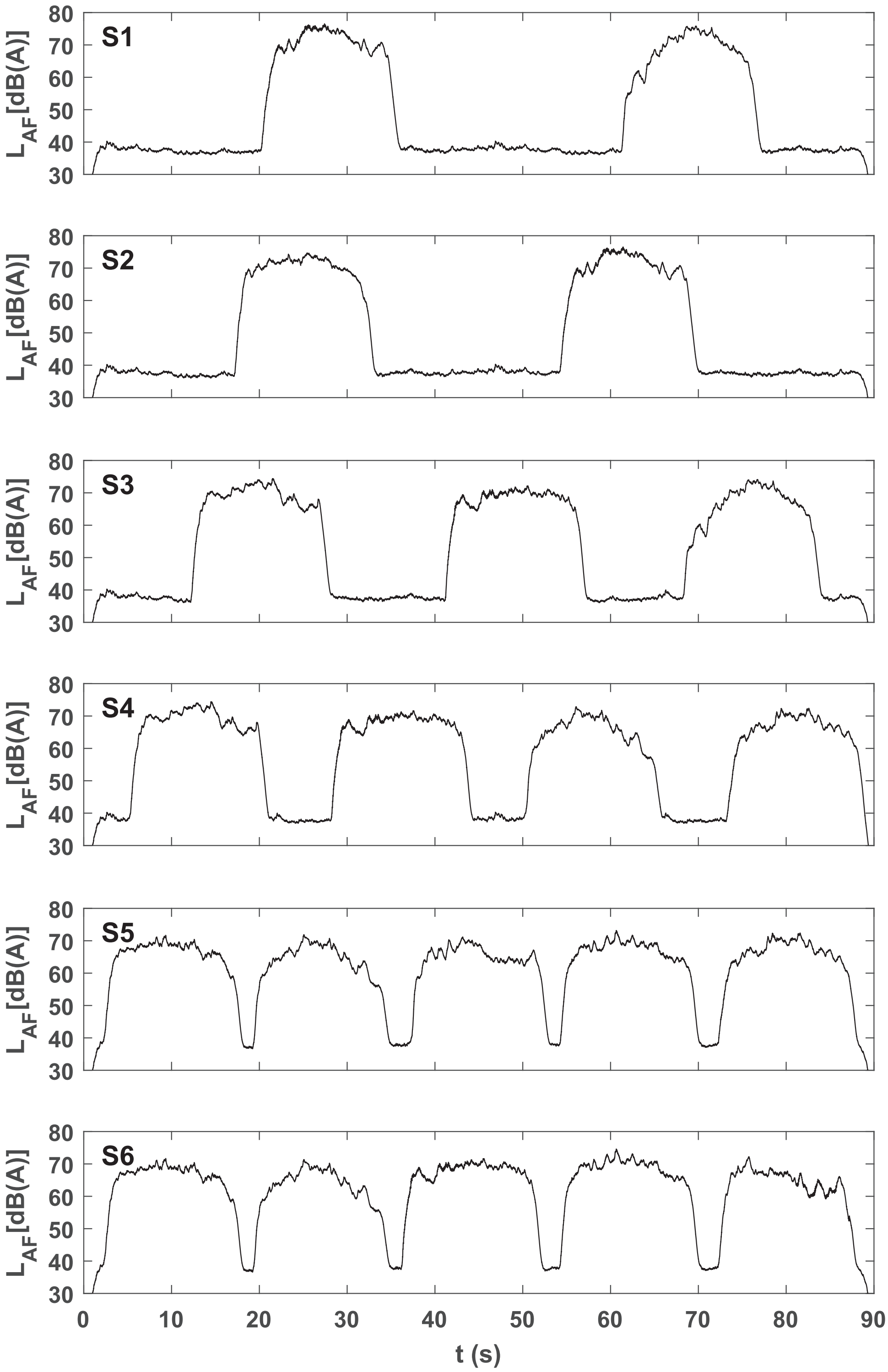

Figure 1. Stimuli's L_{AF} curves. S1 to S2 stand for scenarios 1 to 6, respectively (see Table 1).

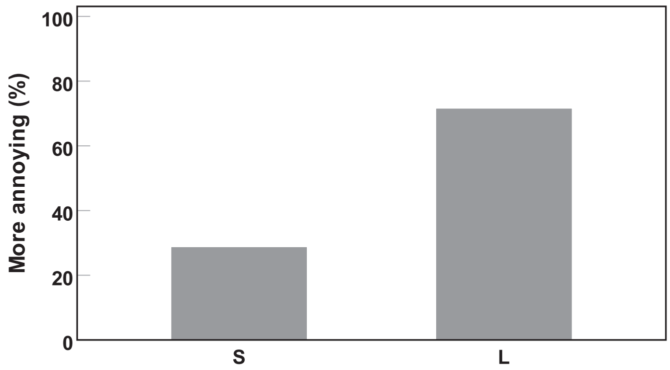

Figure 2. Percentage relative frequencies for "more annoying" stimulus. In a stimuli pair, S and L represented the stimuli with the smaller or the larger number of flight events, respectively.

3.3 Experimental design

A two-alternative forced choice (2AFC) was given to the subjects, asking them whether they found the first or the second sound situation (i.e., stimuli) more annoying (in German: *Finden Sie die erste oder zweite Geräuschsituation lästiger?*). As a graphical help for the subjects, numbers "1" or "2" were displayed on the screen during playback of the first or the second scenario, respectively.

Three pairs of stimuli were prepared for playback. In each pair, one stimulus (L) had a larger number of flybys than the other (S); i.e., "4 vs. 2" (S4 vs. S1), "5 vs. 2" (S6 vs. S2), or "5 vs. 3" (S5 vs. S3). The order of the pairs appearance was randomized for each subject and balanced between subjects. Additionally, the order of scenarios in each pair was randomized for each subject. In order to minimize the primacy and the recency effects, each stimuli pair was played back twice before it was rated. With a short break in between repetitions of stimuli pairs, each repeated pair playback took 6.5 minutes.

Furthermore, the flight direction of the virtual acoustical scenarios was balanced between the subjects; i.e. either takeoffs from right to left and landings from left to right, or vice versa.

3.4 Experimental sessions

The experiment was carried out as an individual focused listening test for each subject. After reading the study information and signing a consent form, the subjects answered the first part of a questionnaire about their hearing and well-being. Subjects made their 2AFC for the three pairs directly after the (repeated) playback of each pair. The listening test took 20 minutes. After the listening test, the subjects filled out the remaining part of the questionnaire about their demographic data.

3.5 Subjects

Fifty-six subjects (22 females and 34 males) participated in the experiment. They declared to have normal hearing and to feel well. They were aged between 18 and 71 yr (median 43 yr).

4 RESULTS

In total, 168 comparisons were collected (i.e., three 2AFCs by 56 subjects). In 120 comparisons (71.4% of the ratings) subjects found the stimulus with the larger number of flight events (i.e., with less quiet time or, equivalently, with a lower CMT or lower IR) more annoying than the other stimulus (Figure 2).

Figure 3 shows the ratings separately for the three stimuli pairs. For all three pairs, the stimulus with the larger

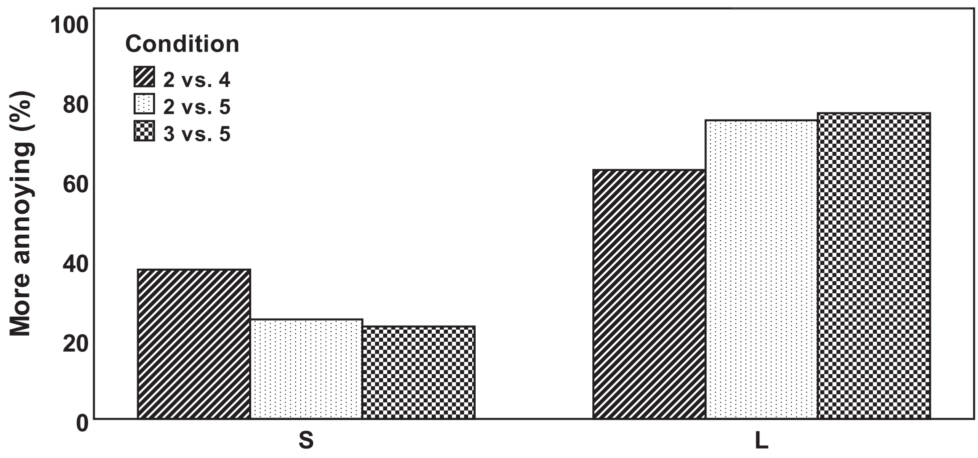

Figure 3. Percentage relative frequencies for "more annoying" stimulus for each pair. S and L represented the stimuli with the smaller or the larger number of flight events, respectively.

number of flight events (L) and a smaller relative duration of quiet periods was chosen to be more annoying. A chi-squared test showed no significant differences between the pairs in predicting the relative frequency of "more annoying" [$\chi^2(2) = 3.33, p = 0.19$]. That is, whereas the results revealed that scenarios with larger number of flights (and less quiet time) were rated, on average, as being more annoying than their counterparts, no significant differences were found between different pairs (i.e., "4 vs. 2," "5 vs. 2," and "5 vs. 3").

To further investigate possible effects of the indicators on annoyance, "relative" measures were coded between the scenarios in the pairs. Percentage relative frequencies for "L more annoying than S" and a series of relative measures between the two scenarios are listed in Table 2 for each pair. The dependence of the binary variable "L more annoying than S" on the relative indicators was analyzed by binary logistic regressions [22] which estimated the probability of "L more annoying than S". Generalized estimating equations [23] were used (SPSS procedure GENLIN) to account for the repeated ratings of the subjects, as they predict a population-averaged response [24, 25]. None of the relative indicators (listed in Table 2) were significantly associated with the probability of "L more annoying than S." This is in line with the above results of the chi-squared test. Nevertheless, relative quiet time, i.e., $T_{\mathrm{quiet,L}}/T_{\mathrm{quiet,S}}$, ($p = 0.053$) and relative CMT, i.e., $\mathrm{CMT_L}/\mathrm{CMT_S}$, ($p = 0.061$) and to a lesser degree also relative IR, i.e. $\mathrm{IR_L}/\mathrm{IR_S}$, ($p = 0.094$) tended to be linked with the probability of "L more annoying than S," while the relative number of flights, i.e. N_L/N_S, was not linked ($p > 0.999$).

Table 2. Relative measures between the scenarios in the pair.

Pair (L vs. S)	**4 vs. 2**	**5 vs. 2**	**5 vs. 3**
Relative quiet time ($T_{\mathrm{quiet,L}}/T_{\mathrm{quiet,S}}$)	0.45	0.17	0.24
Relative number of flights (N_L/N_S)	2.00	2.50	1.67
Relative IR ($\mathrm{IR_L}/\mathrm{IR_S}$)	0.62	0.31	0.47
Relative CMT ($\mathrm{CMT_L}/\mathrm{CMT_S}$)	0.30	0.09	0.16
Percentage relative frequencies for "L more annoying than S"	62.5	75.0	76.8

5 CONCLUSIONS AND OUTLOOK

A psychoacoustic experiment was carried out to investigate the effect of quiet periods in helicopter noise scenarios on the perceived noise annoyance. All scenarios had an equal L_{Aeq} and differed only in the duration of quiet periods and the flyby events' sound levels. The experiment revealed that, in direct comparisons, subjects rated the scenarios with larger numbers of flight events (and thus lesser amount of quiet periods) as more annoying than scenarios with less events. Here, indicators based on the duration of quiet periods such as the Centre of Mass Time (CMT) or the relative duration of quiet periods tended to be particularly effective in predicting the probability of "large number of events being more annoying than small number of events." The results of this study indicate that enabling longer quiet periods should be associated with a lower perceived annoyance. This outcome is in accord with suggestions in the literature [6, 7, 8, 9, 10, 11, 12].

The chosen paired design of this study with two-alternative forced choices does not allow to further link the indicators directly to the perceived annoyance. In a different design (i.e. other than 2AFC chosen here), effects of the measures for the duration of quiet periods (including CMT) on annoyance could be tested directly, e.g., by direct scaling methods based on an annoyance rating using the ICBEN 11-point numerical scale [1]. Furthermore, similar studies could be conducted with road traffic and railway noise stimuli to test whether these noise sources have similar effects. Finally, in future studies non-focused experiments should be performed to test the effects of quiet periods during activities such as reading.

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