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Limits of mixing background sounds to foreground sound samples in psychoacoustic laboratory experiments on noise annoyance

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Abstract

A variety of noise annoyance investigations are conducted as laboratory experiments. To simulate a more natural and realistic scene, it is preferable to add background ambient sound samples to the noise samples. However, possible effects of background sounds on annoyance from foreground sounds should be either minimized or quantified. A laboratory experiment was conducted, in which background ambient sound samples were mixed to foreground helicopter noise samples. In a partially balanced incomplete block design, three factors were varied: noise's sound exposure level (six categories), background sound type (five categories), and background sound pressure level (four categories). Each subject received 40 of the 78 stimuli. Annoyance to each individual 20-s stimulus was rated on the ICBEN 11-point numerical scale. It was investigated whether background sound type and/or level affected annoyance. The major predictor of annoyance was helicopter's sound exposure level. Stimuli containing background sounds with dominant events were associated with higher annoyance ratings than those with less dominant background events or with no background sounds. Increasing background level accentuated the difference between annoyance from stimuli with eventful and less eventful background sounds.

Keywords: Noise annoyance, psychoacoustic experiments, background sounds

1 INTRODUCTION

Use of background sounds is beneficial or, in cases, necessary in a variety of applications in the context of laboratory noise (annoyance) research or virtual acoustics [1]. The following is a non-exhaustive list in this regard [1]:

- Synthetically generated noise samples in the context of virtual acoustics: it is possible to generate noise synthetically by means of emission synthesizers using physical and/or parametric approaches [2, 3, 4, 5, 6, 7]. Adding recorded or synthesized (natural) background sounds to the noise samples helps to increase the degree of realism of the auralization.
- Virtual sound propagation simulation: when propagation filters are used to simulate farther distances [5, 8], recorded background sounds would also be sent to the target distance. Whereas in this case, only the source is aimed to be sent to the target distance, the background sounds are actually supposed to remain close to the observer. This problem can be solved with adding similar background sounds in the observer position [8].
- Auralization of single-channel recordings: when noise is recorded by a calibrated single microphone, as long as the exact momentary positions of the source and the observer are recorded as well, it would be possible to auralize the movement of the source on a multi-loudspeaker system. In this case, however, background sounds contained in the original recording (e.g., birds) would incorrectly move with the foreground noise from one loudspeaker to the other. Since the background sound should commonly be relatively static (with respect to its location), its movement with the noise could be extremely unrealistic and irritating. This might be solved by adding static background sounds to the moving noise which could partially mask the (moving) inherent background sound [8].

- Ambient sound design: when virtual urban scenes are designed or virtual sound walks are simulated, they typically contain one or more background sound sources [9, 10]. It is assumed that sounds of water features, birds, or natural vegetation would improve the virtual living (or urban) environment [11, 12].
- Constant present background sounds in the laboratory experiments: in a psychoacoustic experiment on acoustic comfort, sound pleasantness, or noise annoyance, stimuli are typically played back successively (i.e., one after the other). While the subjects are sitting in a lab, it is asked to imagine they would be sitting in an office, in the garden, in a wind park, at a street corner, or in other scenarios. Thereby, typically no sounds of the imaginary environment—but rather silence—exists in-between the stimuli. It would be much more realistic to have a background sound present in the room for the whole duration of an experiment, from which each stimulus then arises into the foreground [1].
- Contained background sounds in the original noise recordings: although noise recordings are ideally carried out carefully such that they are free of dominant background sounds, still some sort of background sounds are present in any natural or everyday environment. Hence, the recorded foreground sound samples also contain some background sounds. In psychoacoustic experiments on acoustic comfort, pleasantness, or noise annoyance this introduces a possible source of error or bias, which should be controlled for [1].

The examples given above show the relevance/importance of background sounds in virtual audio and psychoacoustic applications. Whereas they justify the vast usage of background sounds in the respective contexts, only a few studies investigated the effects they could have on the perception of the respective scenes.

A number of studies indicated that background sounds (e.g., singing birds, water features, etc.) might improve the acoustic quality of the urban soundscape in presence of annoying noise sources [14, 13, 15, 12]. De Coensel et al. [14] and Nilsson et al. [13] reported that natural water features reduce the loudness of road traffic noise. Bolin et al. [15] suggested similar effects of water sounds with respect to wind turbines noise. It was further reported that water features might reduce annoyance from the road traffic or wind turbines [15, 12]. These reports show potential effects of background sounds on the perception of foreground sounds.

This paper reports a psychoacoustic experiment in which possible effects of the background sound on the annoyance to the foreground noise were investigated.

2 METHOD

2.1 Experimental concept

Short-term annoyance reactions to helicopter noise stimuli were investigated under laboratory conditions, with or without mix background sounds [1]. The observed annoyance ratings correspond to "short-term annoyance" [16, 8] or "psychoacoustic annoyance" [17]. The term "short-term" refers to the time period during and after an acoustic stimulus' playback and before the next stimulus is presented [10].

Stimuli were generated from field recordings [8] of landing helicopters and from background ambient sounds. Three independent variables, i.e., flight event's A-weighted sound exposure level, $L_{\mathrm{AE,F}}$, background sound type (i.e., eventful vs. less eventful), and background sound's A-weighted equivalent continuous sound pressure level, $L_{\mathrm{Aeq,B}}$, were systematically varied to study their individual and combined associations with annoyance [1].

To avoid confusions between the foreground sound (i.e., helicopter noise) and the ambient background sound, in this article, "noise" and "sound" are repeatedly used for these two categories of sounds, respectively [1]. However, it should be noted that, in general, sounds are not to be labeled or prejudged as "noise" per se [18].

2.2 Listening test facility

The experiment was conducted in AuraLab, a listening test facility of the Empa (Swiss Federal Laboratories for Materials Science and Technology), which has a separate listening and control room allowing for audio-visual supervision to comply with ethical requirements [10, 8]. AuraLab satisfies room acoustical requirements

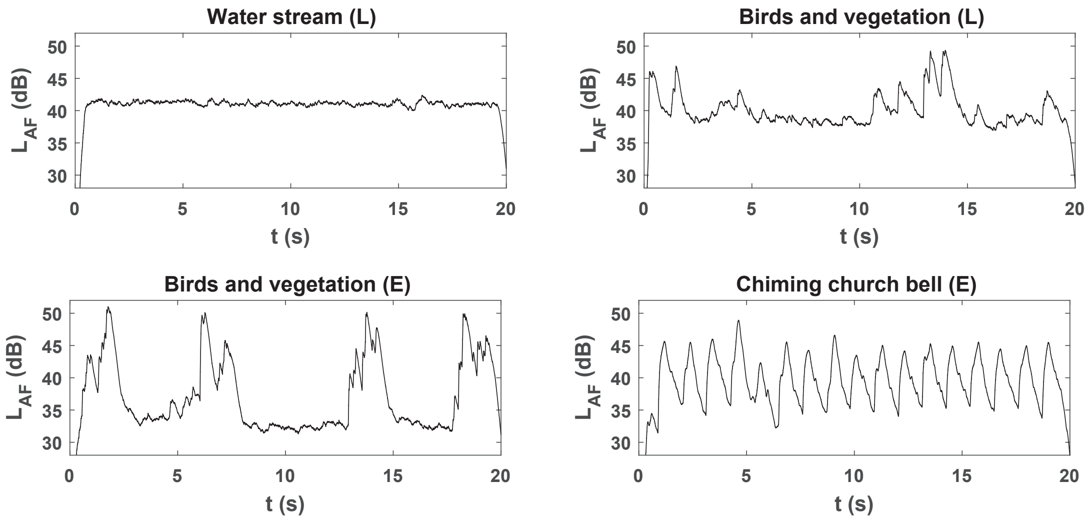

Figure 1. $L_{AF,B}$ of the processed background signals as a function of time. **E** and **L** refer to eventful and less eventful signals, respectively. $L_{Aeq,B} = 41$ dB(A) for all examples shown here.

for high-quality audio reproduction in terms of its background noise and reverberation time. The stimuli were played back through one loudspeaker (KH 120 A, Georg Neumann GmbH, Berlin, Germany) at a distance of 2 m from the listening spot and 0° elevation (subject's ear level) as well as two subwoofers (KH 805, Georg Neumann GmbH, Berlin, Germany). The carpeted floor was covered with additional absorbers.

2.3 Stimuli

2.3.1 Recordings

The helicopter noise samples originated from field recordings of helicopter landings at Grenchen Airport, Switzerland (ICAO code: LSZG) [8]. Single-channel audio recordings were performed by means of a series of microphones (B&K 4188, Brül & Kjær, Naerum, Denmark, and Nor 1227, Norsonic AS, Tranby, Norway) placed 4 m above the ground in the eastern side of the airport, on the left and right sides of the extension of the runway [8]. The six recordings selected 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). Helicopter recordings were done at the sampling frequency of 44.1 kHz and with 16 bit depth [1].

Single-channel recordings of ambient sound were done by means of a microphone (B&K 4006, Brül & Kjær, Naerum, Denmark) placed 2 m above the ground in and around the city of Dübendorf, Switzerland. Background sound recordings were carried out at the sampling frequency of 48 kHz and 24 bit depth [1].

2.3.2 Signal processing and mixing

In addition to the six chosen helicopter noise samples, four background sound extracts were selected: two sounds with dominant events – i.e., a chiming church bell and singing birds (and vegetation) – and sounds with less dominant events – i.e., water stream and birds (and vegetation). Eventfulness in the context of this paper is a measure of signal dynamics and refers to several single dominant events with relatively high energy which arise from a rather low energy background [1]. On the contrary, less eventful sounds are sounds whose momentary sound pressure level do not vary extensively from their A-weighted equivalent continuous sound pressure level, $L_{Aeq,B}$ [19]. The categorization of background sounds into eventful or less eventful was carried out qualitatively, as well as quantitatively (i.e., by means of intermittency ratio, IR [19] and "$L_{10} - L_{90}$"). Figure 1 shows $L_{AF,B}$ of the processed background sound signals as a function of time.

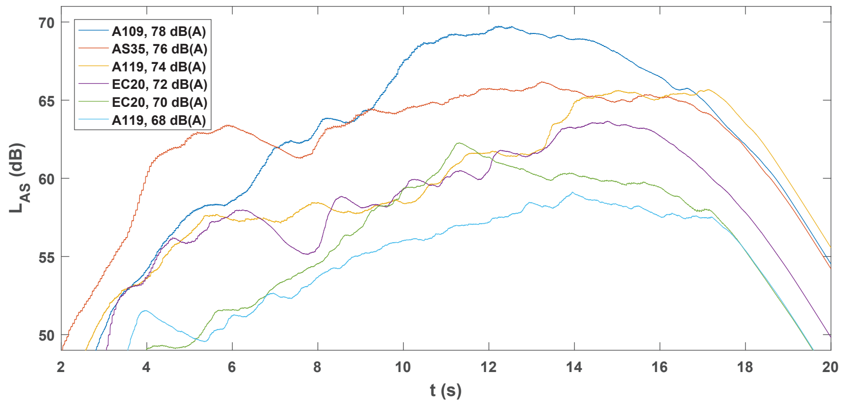

Figure 2. $L_{\mathrm{AS,F}}$ as a function of time for the six flight events (no added background sounds). Helicopter type and $L_{\mathrm{AE,F}}$ of each individual flight event is indicated in the box.

The helicopter as well as the background signals underwent the following processing steps to prepare them for playback in AuraLab [1]. In a first stage of processing, the recordings were calibrated, high-pass filtered ($f_c = 20$ Hz), and low-pass filtered ($f_c = 10$ kHz). The duration of each stimulus was set to 20 s. While background signals were available at a sampling rate of 48 kHz, helicopter signals were upsampled from 44.1 to 48 kHz, which is a requirement of the playback system in AuraLab. Foreground helicopter signals and background signals were then mixed with 16 bit depth [1].

Background and helicopter signals were gated by squared cosine ramps of 0.5 and 4 s, respectively [1]. That is, the background sound was present during the stimulus duration of 20 s and the helicopter sound arose from and faded out into the background sound. The sound pressure levels of the helicopter noise signals ($L_{\mathrm{AE,F}}$) and the background signals ($L_{\mathrm{Aeq,B}}$) were modified to reach the target levels [1]. Beside bass management, which was done by a digital signal processor and crossover filters, most of the processing was carried out with MATLAB R2016b (MathWorks, Natick, USA).

Figure 2 shows $L_{\mathrm{AS,F}}$ as a function of time for the six processed flight events (without any mixed background sounds).

It should be noted that the focus of this experiment was on conditions in which the helicopter noise and the ambient sound were clearly in foreground and background, respectively, i.e., $L_{\mathrm{AE,F}} >> L_{\mathrm{Aeq,B}}$. As a consequence, the following limits were set for the stimuli (and the experimental conditions) [1]:

- $L_{\mathrm{AE,S}} - L_{\mathrm{AE,F}} < 1$ dB(A), whereby S stands for the (mixed) signal/stimulus;
- $L_{\mathrm{ASmax,S}} - L_{\mathrm{ASmax,F}} < 1$ dB(A);
- $L_{\mathrm{Aeq,S}} - L_{\mathrm{Aeq,F}} < 1$ dB(A).

2.4 Experimental design

A partially balanced incomplete block (factorial) design [20] was used with three independent variables [1]: $L_{\mathrm{AE,F}}$ [six levels: 68, 70, 72, 74, 76 or 78 dB(A)], $L_{\mathrm{Aeq,B}}$ [four levels: 6 (i.e., background level of AuraLab in case of no background sound), 34, 41, or 48 dB(A)], and background sounds [five levels: no background sound, water stream (L), birds and vegetation (L), birds and vegetation (E), and church bell (E)]. In total, 78 stimuli were prepared for the experiment:

$$6 \times 3 \times 4 + 6 \text{ (stimuli without background sounds) } = 78.$$

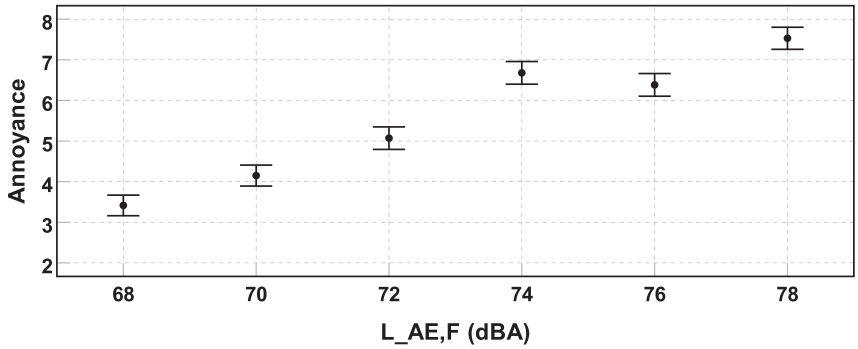

Figure 3. Mean annoyance ratings and their 95% confidence intervals as a function of helicopters' sound exposure level $L_{\mathrm{AE,F}}$. Note that only a portion (2-8) of the annoyance scale (0-10) is shown here.

A-weighted sound exposure levels of the stimuli (i.e., mixed flight and background), $L_{\mathrm{AE,S}}$, were between 68.0 to 78.1 dB(A) (mean $L_{\mathrm{AE,S}} = 73.1$ dB(A)). Furthermore, $20 \leq L_{\mathrm{AE,F}} - L_{\mathrm{Aeq,B}} \leq 72$ dB(A) and $0.0 \leq L_{\mathrm{AE,S}} - L_{\mathrm{AE,F}} \leq 0.8$ dB(A) [1]. The partially balanced incomplete block design consisted of 32 blocks (i.e., subjects), each containing 40 stimuli (i.e., a repeated-measures design).

2.5 Experimental sessions

The experiment was carried out individually for each subject and as a focused listening test. After reading the study information and signing a consent form, the subjects answered the first part of the questionnaire about their hearing and well-being. They were then introduced to the listening test and the test software. Subjects rated their perceived annoyance they associated with each stimulus during or directly after its playback. After the listening test, the subjects filled out the remaining part of the questionnaire about their demographic data [1].

2.6 Listening test software and the annoyance scale

The listening test software (developed at the Empa) guided the subjects through the test and recorded their annoyance ratings [1]. The subjects listened to four orienting and three training sounds before starting the main listening test, in which, for each subject, their 40 stimuli were presented in a random order. They were played back once only, with a 1.5-s break between stimuli.

Short-term annoyance was rated on the ICBEN 11-point scale [21], asking the following question [1]: "When you imagine that this is the sound situation in your garden, what number from 0 to 10 represents best how much you would be bothered, disturbed or annoyed by it?"

2.7 Subjects

Thirty-two self-declared normal hearing subjects participated in the main experiment: 13 females and 19 males, aged between 21 and 50 yr (median 27.5 yr) [1].

3 RESULTS

In total, 1280 annoyance ratings were collected (32 subjects $\times$ 40 stimuli per subject). The effects of the independent design variables on the perceived annoyance was analyzed by linear mixed-effect models (not reported in detail here) [1]. The main predictor of perceived annoyance was the flight event's $L_{\mathrm{AE,F}}$ ($p < 0.001$). Figure 3 shows mean annoyance (and 95% confidence intervals) across subjects and for each $L_{\mathrm{AE,F}}$, averaged over background sound types and levels [1].

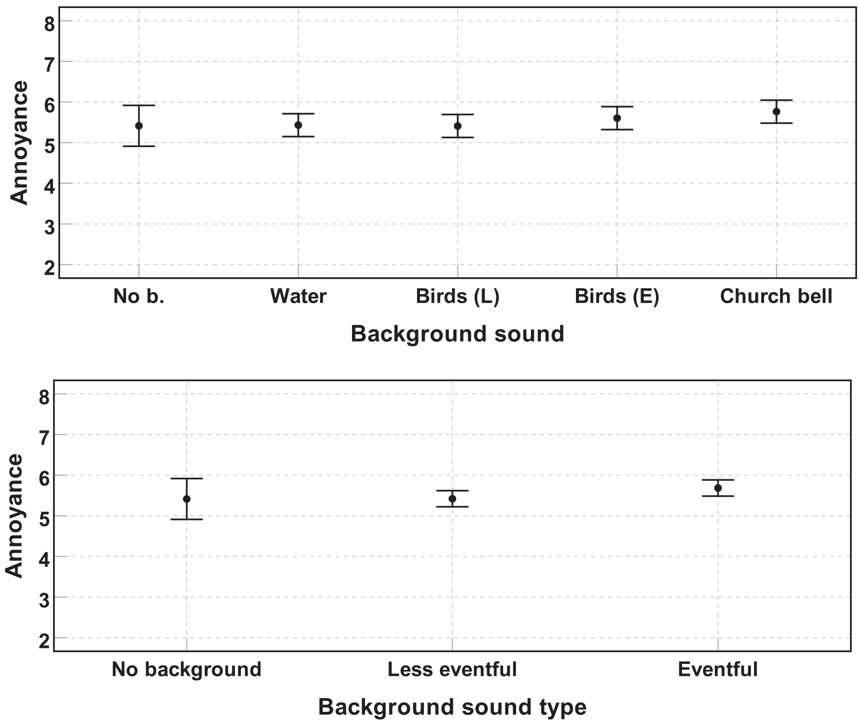

Figure 4. Mean annoyance ratings and their 95% confidence intervals as a function of background sound (above) and background sound type (below). Note that only a portion (2-8) of the annoyance scale (0-10) is shown here.

Background type (i.e., no, L, or E) was a further significant predictor of annoyance ($p < 0.05$). Stimuli with eventful background sounds were more annoying than those with less eventful background sounds. Figure 4 shows mean annoyance (and 95% confidence intervals) across subjects and for each background sounds (above) or type (below), averaged over $L_{\mathrm{AE,F}}$ and $L_{\mathrm{Aeq,B}}$ [1].

Background level ($L_{\mathrm{Aeq,B}}$) showed only in interaction with background type a significant effect on annoyance ($p < 0.05$). That is, with increasing $L_{\mathrm{Aeq,B}}$, annoyance from stimuli with eventful background and less eventful sounds increased and decreased, respectively. No difference could be observed between annoyance from the stimuli with less eventful and those with eventful background sounds at a background level of 34 dB(A). Figure 5 shows mean annoyance (and 95% confidence intervals) across subjects as a function of $L_{\mathrm{Aeq,B}}$; i.e., main effect (above) and the significant interaction with background type (below) [1].

4 CONCLUSION

A laboratory experiment was carried out to quantify the effects of background sounds (mixed with foreground noise) on the perceived annoyance from the foreground noise. Annoyance was found to depend on the noise level, $L_{\mathrm{AE,F}}$, and background type: annoyance increased with increasing $L_{\mathrm{AE,F}}$ and for stimuli with eventful background sounds. Furthermore, background type and $L_{\mathrm{Aeq,B}}$ interacted significantly in predicting annoyance: the difference between annoyance for stimuli containing eventful or less eventful background sounds grow with increasing $L_{\mathrm{Aeq,B}}$. For this experiment – i.e., when $L_{\mathrm{AE,F}} >> L_{\mathrm{Aeq,B}}$ or $L_{\mathrm{AE,S}} - L_{\mathrm{AE,F}} < 1$ dB(A) –, on average, no difference was found between annoyance from stimuli with no background sounds and those with less eventful background sounds. For applications in psychoacoustic laboratory experiments and in order to ensure the experimental validity (with respect to the foreground aircraft noise), the results suggest to use low-level water stream, birds, and vegetation sounds which exhibit a low degree of eventfulness.

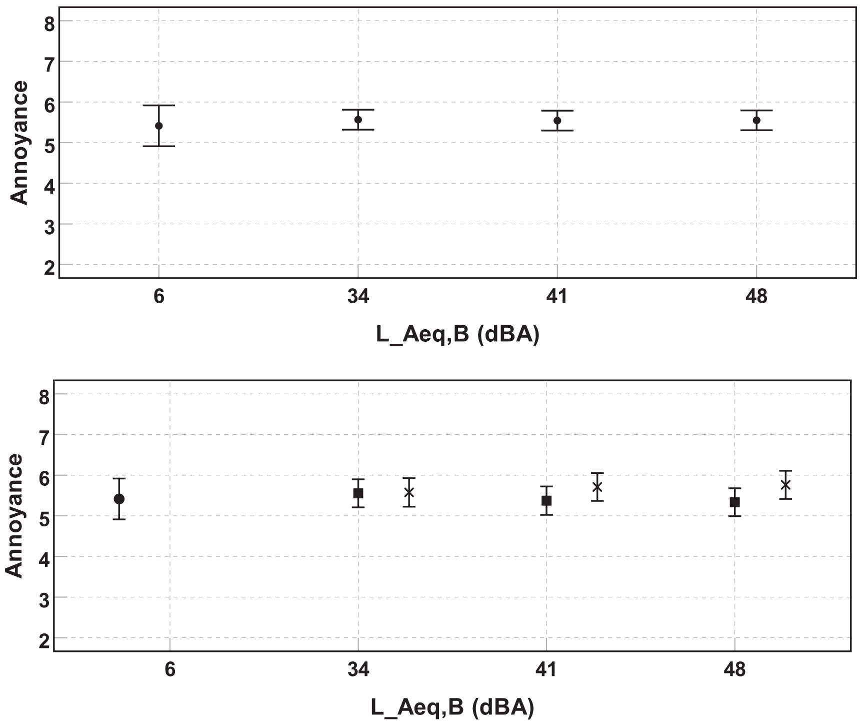

Figure 5. Mean annoyance ratings and their 95% confidence intervals as a function of $L_{\mathrm{Aeq,B}}$ (above). The interaction between background type and level ($L_{\mathrm{Aeq,B}}$) is shown below, whereby circle (●), square (■) and cross (✕) stand for no, less eventful, and eventful background, respectively. Note that only a portion (2-8) of the annoyance scale (0-10) is shown here.

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