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Aircraft noise annoyance modeling: Consideration of noise sensitivity and of different annoying acoustical characteristics

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ABSTRACT

Noise annoyance due to aircraft flyover noise was assessed under laboratory conditions. The main objectives of the study were: (i) to identify influential acoustical features of noise annoyance, (ii) to propose noise indices to characterize these acoustical features and (iii) to enhance annoyance models including influential acoustical and non-acoustical variables. Therefore, a verbalization task was performed by the participants of the experiment to collect their whole impression concerning the aircraft flyover noises for which they rated annoyance. This verbalization task highlights that noise annoyance was influenced by three main acoustical features: (i) the spectral content, (ii) the temporal variation and (iii) the perceived sound intensity. Four combinations of noise indices were used to propose multilevel annoyance models, in combination with the individual noise sensitivity. Noise sensitivity was found to highly contribute to annoyance models and should therefore be considered in future studies dealing with noise annoyance due to aircraft noise. Different combinations of noise indices coupled with noise sensitivity were found to be promising for future studies that aim to enhance current annoyance models.

1. Introduction

In Europe, even if aircrafts have become less noisy over years, air traffic has increased [1]. Therefore, more people are exposed to aircraft noise. Until now, noise management is based on energy-based indices. For example, the European directive 2002/49/EC requires that European cities of more than 100,000 inhabitants produce strategic noise maps for several environmental noise sources, such as aircraft noise. These maps characterize noise exposure using the energy-based index L_{den} – the day-evening-night level.

This index was used by Miedema and Oudshoorn [2] to propose exposure-response relationships: they linked the day-evening-night level of a transportation noise to the percentage of people reporting a certain amount of noise annoyance. These relationships are therefore recommended by the European Commission and used by the World Health Organization to estimate the number of disability-adjusted life years (DALYs) due to noise annoyance [3]. However, different studies showed that these relationships did not allow a good prediction of noise annoyance measured during recent socio-acoustical surveys (*e.g.* [4]).

In addition, several studies demonstrated that such an energy-based index explains only a small part of the whole variance in noise annoyance (*e.g.* [5]). Indeed, noise annoyance is further influenced by numerous acoustical features (*e.g.* spectral distribution of energy [6]) as well as by non-acoustical factors (*e.g.* noise sensitivity [7]).

Concerning aircraft noise, different acoustical characteristics contribute to the whole impression of the noise. For example, Barbot *et al.* [8] performed a preference test on aircraft noises to investigate dimensions of sound perceptual representation. Participants were asked to explain their preference. Three acoustical features of aircraft noise emerged within the descriptive adjectives given by the participants: (i) the timbre aspect, divided into pitch, texture of noise and compound nature of noise, (ii) the temporal aspect and (iii) the intensity aspect.

Several indices have already been used in literature to characterize these acoustical features of transportation noises. For example, the timbre aspect has been characterized using sharpness (denoted as S) for aircraft noise [8], the roughness (denoted as R) for road vehicle noise [9], the total energy of tonal components in high critical bands (denoted as $TETC_{x-y}$) for tramway noise [10,11] and road vehicle noise [12], *etc.* The temporal aspect has

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been characterized using a noise level derivative index (denoted as σ') for aircraft noise [13], the variance of time-varying A-weighted pressure normalized by RMS A-weighted pressure (denoted as *VAP*) for tramway pass-by noise [10,11], the fluctuation strength (denoted as *F*) for aircraft noise [8], *etc.* Finally, the intensity aspect has been characterized using the A-weighted equivalent sound pressure level (denoted as L_{Aeq}) or the loudness (denoted as *N*) for road vehicle noise (*e.g.* [9]).

The aim of the present paper is to enhance annoyance modeling for aircraft flyover noise by considering noise sensitivity and acoustical features that influence noise annoyance. The study is carried out under laboratory conditions for different aircraft flyover noises. After identifying different influential acoustical features, different indices are tested in order to take these acoustical features into account. Then, multilevel regression is performed in order to consider noise sensitivity as an explanatory variable at individual level and relevant noise indices at stimulus level. Multilevel regression analysis allows to identify promising annoyance models. This paper is organized as follows: the listening experiment is described in Section 2, results are exposed in Section 3 and the discussion is given in Section 4.

2. Experimental methodology

The experiment aims to assess short-term annoyance due to aircraft flyover noise in laboratory conditions.

2.1. Stimuli

For the experiment, 12 aircraft flyover noises were recorded in the neighborhood of the international airport Orly (approximately 5 km away in line with the runway), near Paris, France. Aircraft height is less than 1000 m, after take-off. The noises were recorded *in situ* using the ORTF technique in accordance with French standards. The ORTF couple was placed at a height of 1.5 m and at least at 2 m from any reflecting wall. This recording technique used for stereophonic sound reproduction in laboratory was used in previous studies dealing with moving sources (*e.g.* [10,11]) as it is known for its good representation, readability, plausibility and overall reproduction quality for fixed and moving noise sources [16].

The A-weighted equivalent sound pressure level (denoted as L_{Aeq}) of the aircraft flyover noises was measured using a B&K 2250 sonometer. Differences in L_{Aeq} observed *in situ* were kept, resulting in a range from 43.5 dB(A) to 54.6 dB(A). Table 1 gives for each aircraft flyover noise: stimulus duration, 10 dB-down duration (duration of the aircraft noise event during which the instantaneous noise level lies within 10 dB(A) below the highest noise level, *e.g.* [13]), A-weighted equivalent sound pressure level L_{Aeq}, single event noise exposure level (denoted as L_{AE}) and A-weighted maximum sound pressure level (denoted as L_{Amax}).

The duration of the tested stimuli was imposed by the original duration of single aircraft flyover noises recorded *in situ*: in order to present aircraft noise in the same way as it is perceived by inhabitants, a stimulus lasted as long as the aircraft flyover noise was perceptually discernible from the background noise. Durations varied between 22.1 s and 61.5 s. The 10 dB-down duration was also given as this index is often used to describe aircraft noise (*e.g.* [13]). Previous studies demonstrated that stimulus duration has a limited or no influence on short-term noise annoyance. Paulsen [19] showed that stimulus duration of highway road traffic noises ranging from 1 to 80 s had a very limited influence on annoyance judgments. For single urban road traffic pass-by noises, Morel *et al.* [9] and Klein *et al.* [12] found that stimulus duration between 3 and 9 s was not a criterion to formulate annoyance judgments. The same conclusion was drawn by Trollé *et al.* [10,11] for single tramway pass-by noises with durations ranging from 8 to 25.5 s.

No filter simulating facade transmission was applied to the stimuli as wall material and window types have an effect on auditory judgments [17] and the choice of one specific kind of facade might have been too limiting. Thus, the worst noise exposure is considered (*e.g.* [18]) such as being in private outdoor spaces.

2.2. Apparatus

The listening experiment took place in a quiet room with a background noise below 20 dB(A). Stimuli were reproduced employing a 2.1 audio reproduction system consisting of two active loudspeakers (Dynaudio Acoustics BM5A) and one active subwoofer (Dynaudio Acoustics BM9S).

Concerning positioning of participant and loudspeakers, the center of the interaural axis of the participant and the loudspeakers formed an equilateral triangle. This was in accordance with recommendations given by Bech and Zacharov [20]. The loudspeakers were placed at a height of 1.20 m from the floor, and the subwoofer was placed on the floor between the loudspeakers. The user interface was programed using MATLAB©.

An omnidirectrional microphone (GRAS 40AE) was placed at the participant's position in order to record the noise sequences. From the sequence recordings, acoustic and psychoacoustic indices were calculated using MATLAB© and dBSonic software (ACOEM) [21].

2.3. Procedure

Participants were asked to imagine themselves at home while relaxing (*e.g.* reading, watching television, discussing, gardening or doing other common relaxing activities). This procedure has been used in previous works (*e.g.* [22]). Prior to each experiment, the participants were trained. During the training and experiment, the stimuli were presented one by one in random order.

After each stimulus, a reminder of the imaginary situation was presented to the participants and they were asked: "*During your relaxing activity, you hear this noise. Does this noise annoy you?*" ("*Pendant votre activité relaxante, vous entendez cette séquence sonore. Cette séquence sonore vous gênerait-elle?*"). Participants gave ratings on a continuous scale ranging from "0" to "10", with 11 evenly spaced numerical labels and two verbal labels at both ends ("*not at all*" ("*Pas du tout*") and "*extremely*" ("*Extrêmement*")).

At the end of the experiment, the participants performed a verbalization task: they answered two questions: "*Can you tell what you thought about the aircraft* noises?" ("*Pouvez-vous dire ce que vous avez pensé des bruits d'avion?*") and "*If you have found some noise sequences annoying, can you tell us why you found them annoying?*" ("*Si vous avez trouvé des séquences sonores gênantes, pouvez-vous nous dire pourquoi vous les avez trouvées gênantes?*"). If the first answer was very short, the experimenter asked three supplementary questions after the first one, in order to obtain more descriptions from the participant: "*Did the aircraft noise seem to be familiar to you?*" ("*Est-ce que le bruit des avions vous a paru familier?*"), "*Can you describe the aircraft noise?*" ("*Pouvez-vous décrire le bruit des avions?*") and "*In a general way, how do you judge aircraft noise?*" ("*De manière générale, comment jugez-vous le bruit des avions?*"). Then, they filled in a questionnaire with personal items such as non-acoustical factors. For noise sensitivity, participants were asked: "*Would you say you are sensitive to noise in a general way?*" ("*Diriez-vous que vous êtes sensible au bruit en général?*") and they had to make a judgment on a continuous scale ranging from "0" to "10" with two verbal labels at both ends ("*not at all sensitive*" ("*Pas du tout sensible*") and "*extremely sensitive*" ("*Extrêmement sensible*")), a similar scale to the one used to measure noise annoyance.