Perceptual relevance of acoustical parameters in aircraft noise

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This paper focuses on the perception of three main signal components of aircraft sound: multiple pure tones (MPT), blade passing frequency (BPF) and broadband noise. The interaction between these components and their relative impact on noise annoyance still needs to be investigated. The experiment carried out in this study aims at understanding if MPT is a prominent perceptual factor when combined with BPF, and how MPT perceptual prominence changes when MPT and BPF are combined at different gain levels. To address this issue, we used a free sorting task (FST) protocol in which participants have to use their own similarity criteria in order to sort a set of sounds. FST is a simple procedure that allows to reveal the perceptual strategies of participants when they are exposed to a set of complex sounds. Its main advantage is to let the participants free to choose his/her sorting criteria, with very few guidance from the experimenter. From a theoretical point of view, this task is based on perceptual categorization, which is a natural cognitive process used in everyday life. Two sets of 15 sounds corresponding to two types of large aircraft were judged by 57 participants in an isolated sound booth. These data were analyzed using multivariate component analysis (MCA) to identify perceptual factors used by most of the participants to form their categories. Results showed that MPT was always more perceptually salient than BPF, and that BPF and MPT intensity differences were not relevant for the participants.
Keywords: sound perception, free sorting task, aircraft noise

1. Introduction

Despite major improvements in the reduction of aircraft sound level in the past decades, aircraft sound perception still needs to be investigated in order to, *in fine*, better understand noise annoyance. As mentioned in several studies ([1,2] for example), the sound of many aircraft at take-off may be described by a broadband noise (e.g., airframe noise and noise sources from the engine) and two types of tonal components : (1) a multiple pure tones component (MPT) and (2), a blade passing frequency (BPF) made of a single high frequency pure tone. Differences can also be heard between two different types of engine (engine a and b) : a BPF with a fundamental frequency at 1400 Hz versus 3600 Hz respectively, and two different overall spectral envelopes of MPT for each type of engine. In addition, aircraft sound can present spectro-temporal fluctuations generated by the Doppler effect, atmospheric turbulences and ground reflections. Figure 1 illustrates the spectro-temporal differences between the two types of spectral envelope for each type of MPT. Given these two tonal components that are combined together at aircraft take-off, and given that tonal components have an impact on noise annoyance [1,3], the issue addressed by this paper is to understand which tonal component is the most relevant for sound perception without focusing, as a first step, on annoyance.

Many studies on aircraft sound perception focus explicitly on noise annoyance, unpleasantness or specific sound qualities, and much less research have been carried out on aircraft sound perception without mentioning annoyance. In [2], a continuous scale was presented to the participants and they were asked to evaluate the unpleasantness of 30 aircraft sounds synthesized with the same three acoustical components mentioned before. In [1], synthesized aircraft sounds at landing (i.e, without the MPT component) were used and participants were asked to judge unpleasantness of sounds presented in pairs. In [3], recorded aircraft sounds at take-off and landing were used and two types of judgment were asked from the participants : (1) dissimilarity between pairs of sounds on a scale ranging from “no difference” to “extremely different” and (2) preference between the tested sound and a reference sound on a scale ranging from “much more disagreeable” to “much more agreeable”. In [4], a magnitude estimation of loudness, noisiness and annoyance has been performed with nine kinds of noise sources including aircraft noise and other transportation noises. In the experiment ran in [5], the participants were asked to rate several aircraft sounds on a list of 10 terms related to acoustic components of noise (e.g., bearable, booming, buzzing, etc.). And in [6], a field study and laboratory experiment were carried out in which participants had to rate and record their annoyance responses to aircraft flyovers in a 50-min listening session and using a continuous 10-point numerical scale from ‘‘not at all annoying’’ to ‘‘extremely annoying’’.

The main limitation of focusing explicitly on noise annoyance is that it forces participants to focus on a negative feeling, which can be considered as being reductive given that sound perception is not reduced to negative feelings. Running a paired comparison of dissimilarity is indeed an efficient way to study noise perception without focusing on noise annoyance but it remains limited since it forces the participants to focus their listening attention only on acoustical features [7] and does not let them free to choose the criteria that are the most relevant to compare sounds.

In the present study, it has been chosen to use an auditory free sorting task (FST), i.e., a procedure in which participants are asked to sort a set of sounds and to find their own similarity criteria without explicitly naming them, in order to complete the sorting. Via statistical analyses, this procedure is able to reveal the listening strategies used by participants when they are exposed to a set of complex sounds, i.e., to reveal the factors used by participants as being relevant factors for sound perception in this context of sorting sounds. Its main advantage is to let the participants free to choose their own sorting criteria, with very few guidance from the experimenter. More theoretically and according to [8,9], an auditory free sorting task involves listener’s cognitive processes in a way that is coherent with how his/her semantic knowledge is organized in memory through sensory experience. This method has been used to study auditory perception of different types of sounds in different types of contexts such as environmental sounds [10,11,12], musical sounds [13,14,15], soundscapes [16], and speech sounds [17,18].

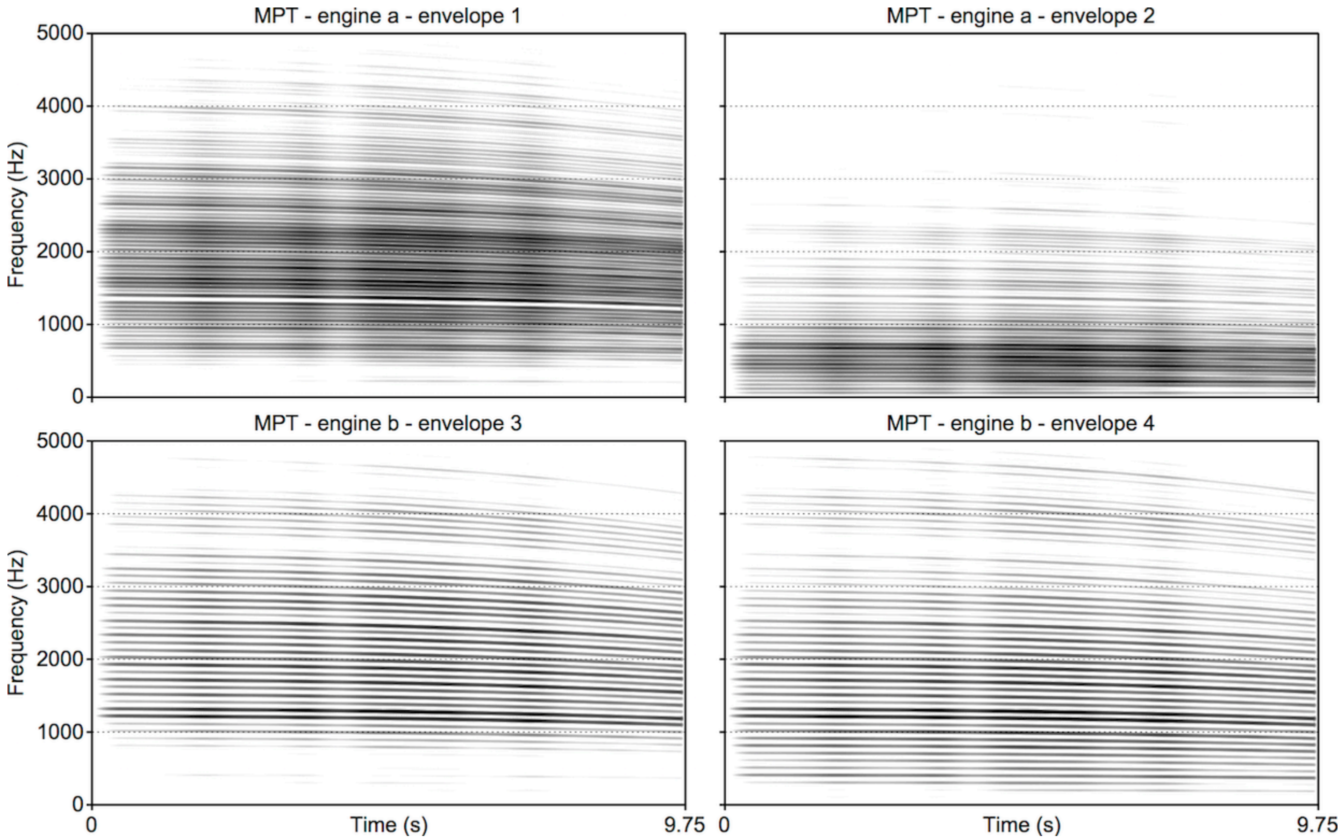

Figure 1: spectro-temporal analysis of the two types of MPT for each type of engine (time resolution = 6 ms, frequency resolution = 5 Hz)

2. Method

2.1 Stimuli

Twenty nine stimuli of synthesized aircraft sounds were used in this experiment using the same synthesizing method as the one presented in [1]. All sounds were artificially produced by adding MPT and BPF components to the broadband noise component. Two types of engines were simulated, each type of engine producing its specific BPF frequency as well as two types of spectral envelopes for MPT. Table 1 presents the different combinations of components used in each of the 29 stimuli. The stimuli with BPF and MPT at +0dB (stimuli named s03, s23, s12 and s09) correspond to the normal conditions of each couple "type of engine" / "MPT envelope". From these normal conditions, experimental conditions were created by combining the broadband noise with different amplifications of BPF and MPT : no MPT and +3dB MPT, no BPF and +6dB BPF. All sounds were 9.75 seconds in duration and were equalized in perceptual loudness in a preliminary experiment, with the reference sound (broadband noise alone) measured at 65 dBA (LAmax) at listening position.

Table 1: combinations of MPT and BPF used to create the 29 stimuli of synthesized aircraft sounds

			MPT engine a - env1		**MPT engine a - env2**		**MPT engine b - env3**		**MPT engine b - env4**	
		No MPT	**+0dB**	**+3dB**	**+0dB**	**+3dB**	**+0dB**	**+3dB**	**+0dB**	**+3dB**
No BPF		s02	s20	s11	s29	s14	s28	s19	s27	s01
BPF	**+0dB**	s08	s03	s06	s23	s16				
1400Hz	**+6dB**	s22	s25	s24	s17	s13				
BPF	**+0dB**	s05					s12	s18	s09	s15
3600Hz	**+6dB**	s07					s04	s10	s21	s26

The stimuli were divided in two sound sets of 15 stimuli corresponding to the two types of engine. Both subsets included the sound named "s02" with no MPT and no BPF.

2.2 Procedure

This experiment is a free-sorting task (FST) in which the participant is free to listen to the sounds as many times as he/she wants and to form as many categories as he/she wants with no minimum or maximum number of sounds in each category. The FST was presented through the open-source TCL-LabX software (http://petra.univ-tlse2.fr/tcl-labx/) that allows the participant to listen to the sounds and freely create categories of sounds by simply moving them inside the software window.

2.3 Equipment

This experiment took place in the platform PETRA that comprises a series of cutting edge audio equipments dedicated to research on sound perception, and a double walled isolated sound booth in which experiments are ran. Participants were seated in front of two Focal Solo 6BE loudspeakers at a distance of 1.50 m, driven by a RME ADI-8 digital to analogue converter and a TASCAM DM3200 mixer.

2.4 Participants

Fifty seven students from the Université de Toulouse volunteered for this experiment and were randomly assigned to one of the two subsets of sounds. Twenty eight participants (17 female and 11 male, mean age 27.1, standard error 5.5) performed the FST with the sound set a (engine a), and twenty nine different participants (18 female and 11 male, mean age 24.4, standard error 2.8) with the sound set b (engine b). All participants reported to have normal or corrected-to-normal vision as well as normal hearing.

3. Results

Each participant created his/her own categories with the fifteen sounds and Table 2 presents a global description of the data outputted by TCL-LabX. It is shown that the average duration of the task was 8 minutes and participants made 4 categories of sounds in average. These data were analyzed using multivariate component analysis (MCA) and hierarchical clustering on principal components (HCPC) with the open-source R software and the FactoMineR package [19]. The perceptual factors used by the participants to form those categories can be deduced from a comparison between the dimensions found by the MCA and the sound parameters used to create the sounds. The MCA analysis also provides a measure of the statistical coherence between participants. In our data, each of the two groups of participants were found to be highly coherent, which means that no between participants analysis was needed. The results for each group of sounds (engines a and b) are then presented in the two following sections.

Table 2: descriptive statistics of data collected in the FST experiment

Statistic	Engine a	Engine b
Number of participants	28	29
Average duration (in sec)	492	486
Standard deviation (in sec)	179	199
Average number of classes	4	4,1
Standard deviation	1,3	1,3
Maximum	8	7
Minimum	1	2

3.1 Sound set a (engine a)

Figure 2 presents the MCA and HCPC analyses for sound set a (engine a, 28 participants) with dimension 1 versus 2 and dimension 2 versus 3. The HCPC analysis gave three groups of sounds that are presented in different colours : MPT envelope 1 (black), MPT envelope 2 (green) and sounds without MPT (red). Each dimension of the MCA explains a percentage of the data variance, and the dimensions are ordered hierarchically. The results show that the first 3 dimensions explain more than 57% of the variance. According to the description of stimuli provided in Table 1, each dimension is interpreted as follows :

- Figure 2 - left shows that dimensions 1 and 2 clearly separate the three groups of sounds given by the HCPC analysis.
- Dimension 1 is representative of 23,6 % of the variance. On this dimension, sounds with MPT envelope 1 are on the left and sounds with MPT envelope 2 are on the right, and sounds without MPT tend to be in the middle even if they are closer to MPT envelope 2. It is then deduced that dimension 1 is mainly explained by the type of MPT envelope.
- On dimension 2, sounds with no MPT are on the right, and sounds with MPT are on the left. Since there is no clear distinction between the two amplifications of MPT, Dimension 2 can be associated to presence/absence of MPT.
- Dimension 3 is less predominant with only 11,8% of explained variance. Stimuli at the bottom of this dimension have no BPF or +0dB BPF (e.g., s02, s29, s14), and stimuli at the top have +6dB BPF (s22, s24, s25, s13, s17). This dimension can be associated to the presence/absence of BPF with no clear distinction between +0dB and +6dB gain.

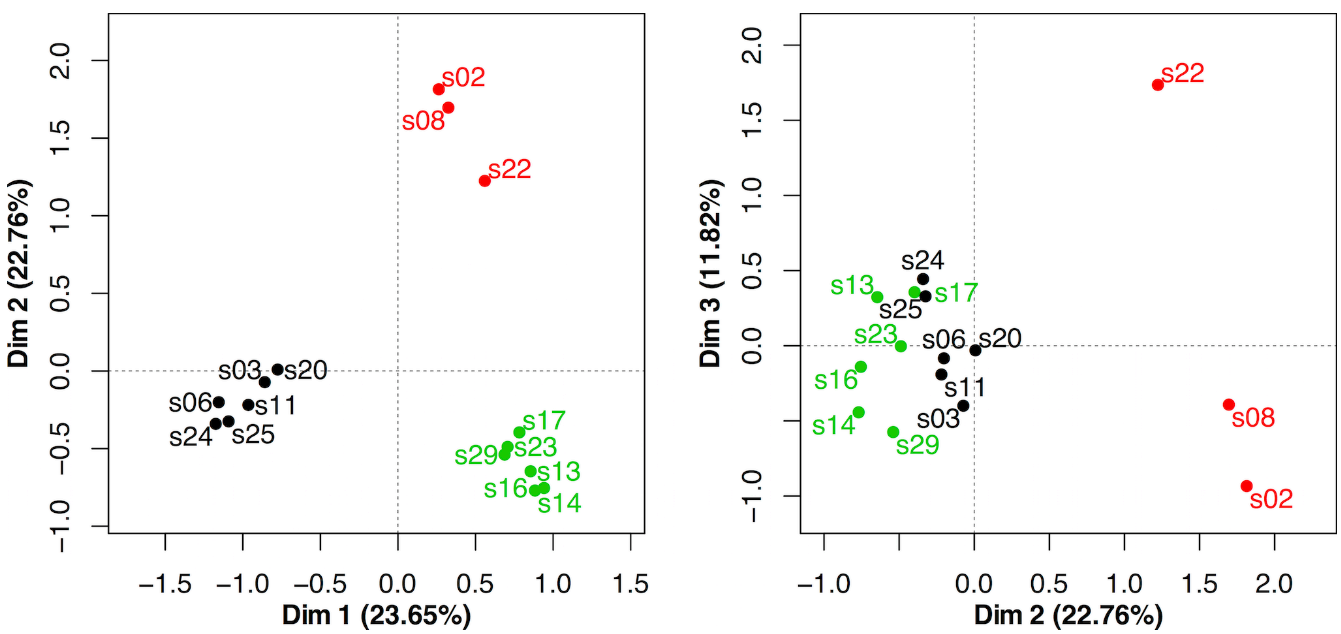

Figure 2: Multivariate component analysis (MCA) of the 15 sounds categorized by 28 participants with sound set a (engine a). Sounds are plotted along dimension 1 and 2 (Left) and along dimension 2 and 3 (Right). The three coloured groups of sounds are given by the hierarchical clustering analysis (HCPC).

3.2 Sound set b (engine b)

Figure 3 presents the results of the MCA and HCPC analyses for sound set b (engine b, 29 participants). According to the description of stimuli provided in Table 1, each dimension is interpreted as follows :

- Dimension 1 is representative of 23,7% of the variance. Sounds in black are on the left of this dimension and all have MPT (+0dB and +3dB gains are not discriminated). Sounds in red and green have no MPT. This dimension is clearly associated to the presence/absence of MPT
- Dimension 2 is representative of 15,6% of the variance and is associated to the presence/absence of BPF : sounds with BPF in the bottom of dimension 2 with no clear distinction between the different gain values, and sounds without BPF on the top of the figure.
- Dimension 3 represents only 11.1% of the variance and no clear link can be made between the sounds position and any acoustical parameter.

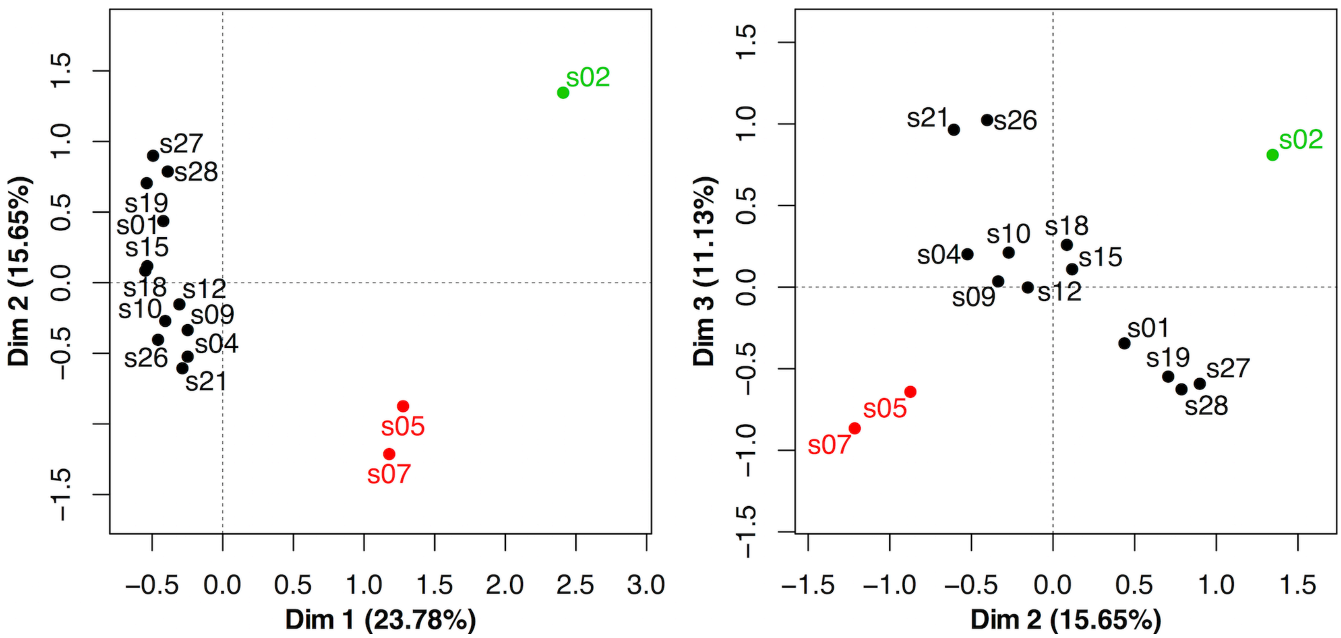

Figure 3: Multivariate component analysis (MCA) of the 15 sounds categorized by 29 participants with sound set b (engine b). Sounds are plotted along dimension 1 and 2 (Left) and along dimension 2 and 3 (Right). The three coloured groups of sounds are given by the hierarchical clustering analysis (HCPC).

4. Discussion

As shown by the MCA and HCPC analyses, for both types of engines, the first dimension that explains most of the variance in the FST data is associated to the MPT component. For the sound set corresponding to the first type of engine, this first dimension is the MPT spectral envelope, and for the second type of engine, the first dimension is associated to the MPT presence/absence. Then the second dimension is associated to : MPT presence/absence for engine a, and to BPF presence/absence for engine b. And finally for the third dimension : it is associated to the BPF gain for engine a and there is no significant association for engine b. In other words, the data collected in the FST highlights the perceptual relevance of each acoustical parameters as well as the hierarchy between the parameters : MPT is more perceptually relevant than BPF for both types of engine. As a complement to previous research measuring the contribution of tonal components to noise annoyance (e.g., [1,2,3]), this result indicates what tonal component, between MPT and BPF, could potentially have a greater impact on noise annoyance.

In addition, for the engine b, participants did not make a clear distinction between the two types of MPT (spectral envelopes 3 and 4), whereas for engine a, the type of MPT spectral envelope was clearly used by participants to form their categories (dimension 1 in the MCA analysis, Figure 2). This result is coherent with auditory contrasts between the different spectral envelopes of MPT that can be illustrated by the cochleagrams shown in Figure 4. The cochleagram is a psychoacoustical illustration of sound that represents a simulation of the excitation pattern produced by the sound in the cochlea. This figure shows a clear auditory contrast between the two envelopes of engine a (Figure 4, left), whereas the two types of envelopes are much less contrasted for engine b (Figure 4, right).

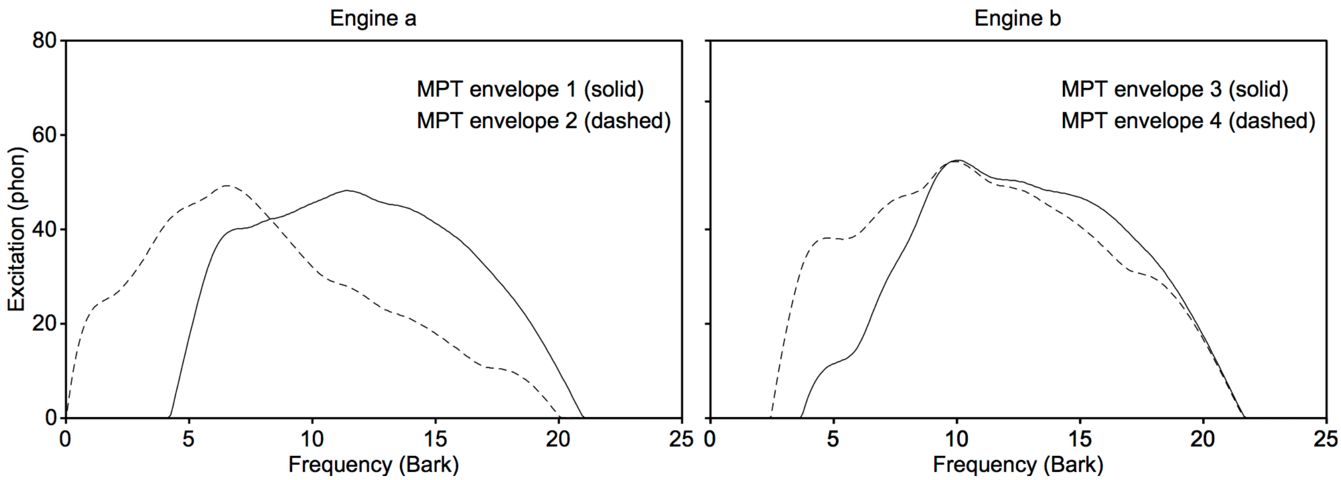

Figure 4: cochleagrams of MPT component with each spectral envelope and for each type of engine : engine a (left) and engine b (right).

Then, results also show that for both types of engines, and for both MPT and BPF, the gain level differences are not clearly distinguished since they do not lead to different categories made by participants. This means that in this experiment, MPT and BPF intensity differences were not perceptually relevant for the participants. This last result is coherent with a previous work [2] in which only a 12 dB gain reduction of BPF or MPT reduced unpleasantness significantly.

5. Conclusions

In this study, two groups of participants have been asked to perform a free sorting task (FST), each of them with one set of 15 synthesized aircraft sounds representative of two types of aircraft engine. Three acoustical parameters have been used in the sound synthesis : type of spectral envelope and gain amplification for the multiple pure tone (MPT) component, and gain amplification for the blade passing frequency (BPF) component. The analysis of the collected data has highlighted the perceptual relevance of each acoustical parameter, as well as the perceptual hierarchy between these parameters. Conclusions can be drawn for each type of engine : (1) for the first type of engine, the hierarchy is MPT envelope > MPT presence/absence > BPF presence/absence, and (2) for the second type of engine, the hierarchy is MPT presence/absence > BPF presence/absence. Indeed, the different gain amplifications were not perceptually relevant for the participants, and instead it was the presence or absence of MPT or BPF. From a set of complex sounds, this study has demonstrated that a free sorting task can be efficient in finding the perceptual relevance of different acoustical parameters, and this can be useful for future studies dedicated to understanding aircraft noise annoyance.

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