How a Loudness Halving Affects the Perceptual Space for Tonal Fan Sounds

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Introduction

Fan sounds are often heard in daily life and can be rather unpleasant, especially when containing audible tones. In such cases, a level reduction usually leads to more pleasant sounds because of the tight link between sound pressure level, perceived loudness, and the evaluation of a sound. To characterize the contribution of sound character and the related different perceptual attributes to the assessment of pleasantness of sounds in detail, semantic differentials are often used. In such studies, (A-weighted) sound pressure levels of stimuli are typically equalized to reduce the dominant impact of perceived loudness, driving the unpleasantness because of the aforementioned tight link [1, 2, 3]. This equalization is, in most cases, an accepted synthetic modification of measured or recorded sounds which originally varied in terms of sound pressure level, although loudness equalization was also found to affect the perceptual representation of timbre [4]. Most studies with a semantic differential focus on a single unified level of the stimuli and it remains unclear how the perceptual characteristics of the sounds would be affected by a level change. In this study, tonal fan sounds were rated by 16 participants with a semantic differential consisting of 21 perceptual attributes. In two experiments performed on separate days, the level of the stimuli was either 55 dB(A) or 45 dB(A), corresponding roughly to halving/doubling of the perceived loudness.

Methods

Experimental Setup

The listening experiments were carried out in a double-walled listening booth. The fan sounds were presented diotically with open headphones (Sennheiser, HD 650) and were driven by an external audio interface (RME, Fireface UCX). MATLAB (The Mathworks) was used to randomize the playback of the signals and the order of the adjectives. The playback level was calibrated using an artificial ear (B&K 4153) with a microphone capsule (B&K 4134) connected via a microphone pre-amplifier (B&K 2669) to a measurement amplifier (B&K 2610). The entire set-up as well as the user interface for the listening experiments were the same for both SPL conditions and the same as in Claaßen *et al.* [3] to ensure the same experimental conditions.

Stimuli

The stimulus set consisted of a selection of fan noise recordings and additional synthetic sounds. The recordings were selected from an original set of 104 fan sounds. The fan sound recordings differed in the type of fan (axial, radial, cross flow), the number of blades (ranging from 5 to 31), the diameter (ranging from 75 mm to 3160 mm), and RPMs (ranging from 746 to 4739) resulting in a wide range of sound characteristics. Out of this database, 20 fan sounds were selected by sorting out sounds with very similar sound characteristics, maintaining the range of sound characteristics in principle while reducing the number of recordings to a reasonable value. The 20 recordings were complemented by four additional synthetic sounds from Claaßen *et al.* [3]. The four added sounds inhered one sound that contained only a broadband background noise without prominent tones, two sounds with an embedded single tonal component (at 60 Hz or 180 Hz, low TNR) and a sound containing a complex tone with eight partials and a fundamental frequency of 300 Hz (high TNR). All sounds have been cut to a duration of 5 seconds for the listening experiments and prepared with a SPL of 55 dB(A) and 45 dB(A).

Semantic Differential

The adjectives for the semantic differential were chosen by several iterations of listening through the collection of fan sound recordings and noting down all potential items that came into the listeners mind. The list of collected attributes revealed denotative, connotative, and evaluative adjectives and, despite the different stimulus context, many attributes were also part of the work of Claaßen *et al.* [3], suggesting a general suitability of their semantic differential also for this collection of tonal fan sounds. To enable a direct comparison of those synthetic sounds taken from the work of Claaßen *et al.*, the same semantic differential consisting of 21 adjective scales, as used by Claaßen *et al.*, was chosen. The semantic differential is similar to other studies dealing with fan sounds [2]. The ratings were collected on a 7-point categorical scale from one to seven. German language was used in the listening experiment and English translations are reported here. Because the two German adjectives "brummend" and "summend" both translate to "humming" in English, an asterisk is used continuously to indicate "summend" in the following.

Procedure

The listening experiments for the two SPL conditions were carried out on two separate days to avoid that the participants directly notice the attenuation/increase of the SPL. Each session had a duration of approximately 1.5 hours. Ten participants did the 55 dB(A) condition first while the other six participants started with the 45 dB(A) condition. Prior to the experiment, the participants were informed about the experiment by written instructions and a list containing all 21 adjective scales. After the instruction, an orientation phase took place in which the participants listened to each of the sounds for a duration of 5 s in random order. In the following measurement phase of the experiment, each signal was played repeatedly until all adjective scales were rated on the 7-point categorical scale. To avoid bias effects, the order of the stimuli and adjective scales were randomized for each participant.

Participants

A total of 16 participants (6 women, 10 men) performed in the listening tests. Their average age was 25 years (ranging from 20 to 36 years). They were mainly students of the University of Oldenburg and received a compensation of 10 Euros per hour for their efforts. They reported no hearing impairment and were native German speakers. All of them already took part in the study of Claaßen *et al.* [3] and had little to no experience with listening experiments beyond that. The Committee for Research Impact Assessment and Ethics of the University of Oldenburg had no objections against this study (ethics application EK/2021/073).

Results

Influence of loudness halving on semantic profiles

Figure 1 shows mean semantic profiles averaged across the three most pleasant and the three most unpleasant sounds of the stimulus set to demonstrate the effect of loudness halving for them. The sound pressure level of 45 dB(A) is plotted with a dashed connecting line and triangles pointing downward, the 55 dB(A) condition is plotted with a continuous connecting line and triangles pointing upward.

For the most pleasant sounds, the differences between the semantic profiles for the two SPL conditions are all smaller than the standard error. Nevertheless, the remaining very small differences indicate that for the lower sound pressure level the sounds are perceived to be more pleasant, quieter, more repressible, softer, less powerful compared to the higher SPL condition, as expected. For these sounds the loudness doubling apparently has only little impact on the description and evaluation of the sounds.

For the most unpleasant sounds, there are considerable differences in the ratings especially for some sound describing items. The level reduction by 10 dB renders the sounds less humming, less vibrating, less rumbling, less booming and less propeller-like and the sounds were judged to be smoother and quieter while the sounds were still similarly jarring and beeping like the sounds with a 10-dB higher level. These latter attributes seem to be more important for the pleasantness rating which also barely changed with the level reduction.

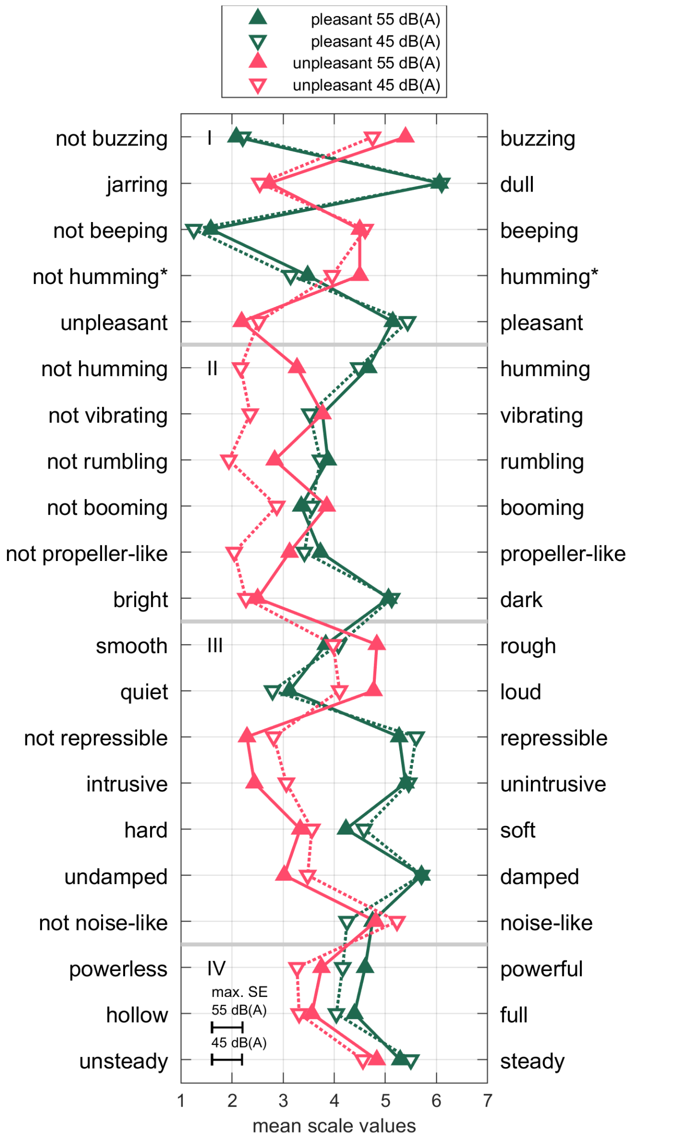

Figure 1: Mean semantic profiles across the 3 most pleasant and most unpleasant sounds at 45 dB(A) and 55 dB(A). The horizontal lines and capitalized Roman numerals indicate the perceptual dimensions identified for the 55 dB(A) condition.

Influence of loudness halving on perceptual space

To explore the perceptual space of the fan sounds for the two sound pressure level conditions, a principal component analysis (PCA) was performed on all adjective scales, each. The sampling adequacy of the measured data was tested with the Kaiser-Meyer-Olkin-Criteria. A value of $KMO = 0.87$ ("meritorious") was obtained for both sound pressure level conditions. In addition, Bartlett's test of sphericity was also significant for each data set, rejecting the null hypothesis which assumed that the variables are uncorrelated and supporting the suitability of the data sets for a PCA. Analyzing the data with a factor analysis leads to similar results.

To decide on the number of retained factors, a parallel analysis was performed for each of the SPL conditions, suggesting four components for the 55 dB(A) condition and only three components for 45 dB(A) condition. The

Table 1: Results of the PCA for 55 dB(A): Varimax-rotated component matrix . For clarity reasons factor loadings ≤ 0.4 are omitted.

perceptual dimension	adjective scale	component I	component II	component III	component IV
I unpleasant / jarring	not buzzing - buzzing	-0.78			
	jarring - dull	0.74			
	not beeping - beeping	-0.66			
	not humming* - humming*	-0.62			
	unpleasant - pleasant	0.62		0.58	
II humming / vibrating	not humming - humming		0.77		
	not vibrating - vibrating		0.76		
	not rumbling - rumbling		0.73		
	not booming - booming		0.62		
	not propeller-like - propeller-like		0.59		
	bright - dark	0.55	0.58		
III rough / loud	smooth - rough			-0.70	
	quiet - loud			-0.69	0.41
	not repressible - repressible	0.57		0.62	
	unintrusive - intrusive	-0.61		-0.61	
	hard - soft			0.55	
	undamped - damped	0.41		0.48	
	not noise-like - noise-like			-0.42	
IV powerful	powerless - powerful				0.76
	hollow - full				0.68
	unsteady - steady				0.49
	explained variance:	18%	16%	15%	9%

Table 2: Results of the PCA for 45 dB(A): Varimax-rotated component matrix. For clarity reasons factor loadings ≤ 0.4 are omitted.

perceptual dimension	adjective scale	component i	component ii	component iii
i unpleasant / jarring	jarring - dull	0.79		
	not buzzing - buzzing	-0.77		
	unpleasant - pleasant	0.75		0.40
	unintrusive - intrusive	-0.74		-0.40
	not repressible - repressible	0.72		0.47
	not beeping - beeping	-0.67		
	undamped - damped	0.62		
	not humming* - humming*	-0.53		
	quiet - loud	-0.49		-0.43
ii humming / vibrating	not humming - humming		0.79	
	not rumbling - rumbling		0.78	
	not vibrating - vibrating		0.75	
	not booming - booming		0.70	
	bright - dark	0.46	0.64	
	not propeller-like - propeller-like		0.58	
	powerless - powerful		0.55	
	hollow - full		0.52	
iii rough	smooth - rough			-0.71
	unsteady - steady			0.55
	hard - soft			0.52
	not noise-like - noise-like			-0.47
	explained variance:	23%	19%	11%

varimax-rotated component matrices are shown in Tab. 1 for 55 dB(A) and in Tab. 2 for 45 dB(A).

Based on the loading of the attributes, the four components for the 55 dB(A) condition in Tab. 1 can be interpreted as the perceptual dimensions (I) unpleasant / jarring, (II) humming / vibrating, (III) rough / loud and (IV) powerful. For the level reduction down to 45 dB(A) shown in Tab. 2, the third dimension (III) reduces down to only four attributes (smooth-rough, unsteady-steady, hard-soft and noise-like) and can be interpreted as the (iii) rough dimension. Two items (powerless-powerful, and hollow-full) of the fourth dimension (IV powerful) blend into the humming dimension (ii) for the 45 dB(A) condition, which seems to be rather unrelated to the evaluation of the sounds. In both level conditions, the attributes buzzing, jarring, beeping, and humming* load onto the first component and seem to be important for the unpleasantness of the sounds.

Discussion

In their original work, Osgood *et al.* [5] identified three typical dimensions (Evaluation/Pleasantness, Potency/Dominance and Activity/Arousal), often abbreviated as EPA structure. Regarding the present results, the components (I) and (i) can be clearly identified as the Evaluation/Pleasantness dimension. The Potency/Dominance dimension often contains attributes like hard and rough and therefore, the components (III) and (iii) seem to reflect this aspect. The Activity/Arousal dimension is split onto two components (II) and (IV) for the 55 dB(A) condition while it is only a single component (ii) in the 45 dB(A) case. A split of the Activity/Arousal dimension onto two components was also found in a study by Töpken *et al.* [6] for multi-tone sounds rated at 70 dB(A) and in a study by Schäffer *et al.* [7] for wind turbine and broadband sounds rated at 40 dB(A). Thus, it seems as if the unification of this dimension onto a single component cannot solely be attributed to the level reduction. Nevertheless, the different number of components for the two conditions is generally in line with a change of the timbre space resulting from loudness equalization in the study of Susini *et al.* [4].

In the present work, attributes related to the low frequency content (humming, rumbling, booming, etc.) load onto a distinct factor and do not seem to be directly related to the evaluation and unpleasantness of the sounds, which is similar to prior studies on fan sounds [1, 3]. The perceptual dimensions identified here are in general similar to those found by Feldmann and Carolus [2]. However, the components in the present case have a mixture of loadings of denotative, connotative and evaluative attributes, enabling an identification of links between them, while the dimensions identified by them are purer in terms of the loading attribute types making them easier interpretable.

Conclusion

The analysis of the ratings with a principal component analysis indicates slightly different perceptual spaces with four dimensions at 55 dB(A) and three dimensions at 45 dB(A). The lower number of dimensions retained by the PCA for 45 dB(A) and the marginally smaller amount of variance explained by these factors might be an indication that the dimensions not related to evaluation are slightly less distinct compared to the 55 dB(A) condition.

For the most pleasant sounds of the investigated sound set, the pleasantness rating and the semantic profile barely changes for the level reduction of 10 dB. For the most unpleasant sounds of the set, several sound characteristics become less pronounced, while the unpleasantness rating and the attributes linked to the evaluation barely change. In both level conditions, the average ratings cover similar ranges of the scales suggesting that the scales were used and should also be interpreted rather as relative and not as absolute scales.

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