THE RELATIONSHIP BETWEEN PERCEPTUAL DIMENSIONS OF FAN NOISE AND PATTERNS OF THE SPECIFIC LOUDNESS

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SUMMARY

The aim of this study is a determination of the perceptual dimensions of fan noise, an identification of the dimensions which are relevant for the (un-)pleasantness of fan noise and the development of (psycho-)acoustic parameters reflecting the most relevant perceptual dimensions. Based on two separate factorial analyses of fan noise ratings, six perceptual dimensions and five groups of sounds were identified. An analysis of the specific loudness reveals distinct patterns for the three major groups of sounds which also differ considerably in terms of their pleasantness ratings.

INTRODUCTION

Fans are one of the noise sources which is perceived by humans in daily life. In many use cases, the generation of sound is inevitable and the resulting fan noise can have a rather unpleasant sound character, which may contribute to the annoyance of fan noise. For a successful development of more pleasant fan sounds it is therefore necessary to understand the variety of perceptual aspects constituting the perceptual space of fan noise beyond current single values like the A-weighted sound pressure level [1]. To determine the dimensions of the perceptual space, a specifically developed semantic differential combined with a factorial analysis of the data is a commonly used approach [2, 3].

Feldmann et al. collected adjectives from nine acoustic experts for the description of fan sounds to compose a semantic differential for fan noise consisting of 37 items [4]. The factorial analysis of ratings of eight fan sounds with the developed semantic differential by 45 participants revealed five perceptual dimensions which were denoted “quality”, “spectral content I”, “temporal structure”, “power” and “spectral content II”. Sung et al. collected descriptors for 24 different heating, ventilation, air conditioning and refrigeration (HVAC&R) sounds which are mainly consisting of the fan noise [5]. Based on the descriptors, a semantic differential with 17 items was compiled which was used to collect ratings of 36 sounds. Sung et al. identified four dimensions denoted "loudness", "tonal/sharpness", "irregular/fluctuation" and "not musical" with a factor analysis of the data [6]. Minard et al. investigated 60 HVAC sounds in the context of car interior noise with a semantic differential consisting of 12 adjective scales [7]. They identified three perceptual dimensions which were associated with the "unpleasantness", "sharpness" and "fluctuation" of the sounds.

The aim of this study is a characterization of the dimensions underlying the perception of fan noise, the identification of the major dimensions which are relevant for the evaluation of fan noise and the identification of objective parameters enabling a description of these perceptual dimensions. The overarching goal of the project is a model of the acoustic quality for fan sounds based on objective parameters. The present study is based on a large set of overall 35 different fan signals, provided by eight fan manufactures and one research institute, including the eight signals from Feldmann et al. [4]. In contrast to the study of Feldmann et al. which was based on adjectives delivered by experts in acoustics, the items for the present semantic differential were collected with non-expert participants, here.

METHOD

Overall, 35 fan noise signals were rated in listening test by 45 volunteers. The sounds were rated on 29 adjective scales which were composed based on two pre-experiments. In these pre-experiments, adjectives for the description of a larger set of 57 different fan sounds were collected. Based on the collected items, 106 adjective pairs were composed and rated in terms of their suitability for the characterization and evaluation of fan sounds. The most suitable adjective pairs together with some items from the literature were used in the semantic differential of this study consisting of 29 adjective scales.

Procedure

Listening experiments with a semantic differential were carried out in two sessions on different days separated by about one week. Each session started by handing out written instructions to the participants and a clarification of possible open questions. In addition, some general information about the experiments was given and also written consent was collected from the participant at the beginning of the first session. After this introduction, the listening experiment took place inside a sound proof booth. In an orientation phase, the participants listened to all 35 fan noise signals and read all 29 adjective scales of the semantic differential. After the orientation, one of two sets consisting of 18 sounds was rated with respect to all 29 adjective scales one by one. The adjective pairs marked the ends of a horizontal seven-point categorical scale. The presentation order of the sounds and the order of the adjective scales were randomized as well as the direction of the scales. English translations of the originally German adjective pairs are given in Table 1 in the results section. A short interview and a questionnaire outside the listening booth concluded each session.

Stimuli

Overall 35 different fan noise signals were used for the listening tests. The signals were microphone recordings of 13 axial fans, 20 radial fans and 2 drum impeller sounds. The technical specifications covered broad ranges of fan diameters (146 - 2818 mm), rotation speeds (550 - 4481 rpm) and blade numbers (5 – 59 blades). The fan sounds were chosen to cover a broad range of different fan types and respective locations in the Cordier-Plot including sounds recorded from test bench measurements and also of installed fans. The signals were technically structured into 13 categories of up to eight signals which were provided by eight different manufacturers and the University of Siegen. The eight signals which were used by Feldmann et al. [4] were also part of the signals in this study. To reduce the duration of the listening experiment reasonably, the signals were split into two sets of 18 sounds, each. One of the signals (00-h1) was repeatedly measured (identified as 00-

h2) as a part of each of the two sets. The two sets were as good as possible balanced in terms of sound characteristics and technical specifications (manufacturers, fan types, diameter ranges). The duration of each signal was five seconds and the playback level was 55 dB(A). Each signal was repeatedly presented with a short break of half a second until the ratings on all 29 adjective scales had been collected.

Listening setup

The listening experiments took place in a sound proof booth with a background level of about 17 dB(A). The signals were presented diotically over open headphones (Sennheiser, HD 650) which were driven by the headphone output of an external audio interface (RME, Fireface UCX) connected to a computer. The presentation of the audio signals and the collection of the ratings were realized in MATLAB (The Mathworks). The presentation level of the signals was calibrated to 55 dB(A) using an artificial ear. The calibration was electrically checked on each day by measuring the output voltage of the headphone output.

Participants

A total of 45 volunteers (23 females, 22 males), mainly students and employees of the University of Oldenburg, participated in the experiments. The mean age of the participants was 25 years. About 50% of the participants were not experienced with listening tests at all; the other half of the participants already took part in other listening tests before.

RESULTS

Perceptual dimensions of fan noise

To determine the perceptual dimensions, one factor analysis (principal component analysis, PCA) was conducted on the adjective scales defined by the ratings of all sounds by all participants. The Kaiser-Meyer-Olkin (KMO) measure of sample adequacy (KMO=0.93) and the Bartlett test of sphericity ($\chi^2(406)=23035$, $p<0.01$) support the suitability of the data set for a factor analysis. Based on the Kaiser criterion, six factors were extracted which explain 62% of the total variance. Table 1 shows the results of the first PCA as the Varimax-rotated component matrix.

The first factor I shows high loadings mainly for the evaluative adjective scales like e.g. *unpleasant-pleasant*, *not disturbing-disturbing*, *not annoying-annoying*, *unbearable-bearable* and *obtrusive-negligible*. In addition, also the rather descriptive item *soft-loud* is loading onto this factor. It can be regarded as the “pleasant” dimension. The second factor II shows high loadings of items related to the low frequency content like e.g. *not humming-humming*, *bassless-bassy*, *not droning-droning* and *not booming-booming*. It is considered as the “humming/bass” dimension. The third factor III has high loadings of the items *not buzzing-buzzing*, *not squeaking-squeaking* and *jarring-dull*. It is interpreted as the “shrill” dimension. The fourth factor IV shows high loading of the items *irregular-regular*, *monotone-varied* and *single sound-mixture of sounds*. This factor is denoted “monotone”. Factor five V has high loading of the adjectives *hollow-full*, *not reverberant-reverberant* and *undamped-damped* which is treated as the “reverberant” dimension. The last factor VI collects the two remaining items *not noise-like-noise-like* and *slow-fast*.

Table 1: Varimax rotated component matrix of the PCA conducted on the 29 adjectives. The six extracted factors can be characterized as (I) "pleasant", (II) "humming/bass", (III) "shrill", (IV) "monotone", (V) "reverberant" and (VI) "noise-like". Factor loadings smaller than 0.4 were omitted for clarity reasons.

adjectives scales	component					
	I	II	III	IV	V	VI
unpleasant - pleasant	-0.88					
not disturbing - disturbing	0.87					
not annoying - annoying	0.87					
unbearable - bearable	-0.86					
obtrusive - negligible	-0.84					
inconspicuous - conspicuous	0.73					
not noisy - noisy	0.64					
agitated - calm	-0.59			-0.45		
soft - loud	0.50					
not humming - humming		0.79				
bassless - bassy		0.79				
not droning - droning		0.75				
not booming - booming		0.74				
not roaring - roaring		0.64				
not vibrating - vibrating		0.64				
powerless - powerful		0.58				
low - high		-0.56	0.55			
not propeller-like - propeller-like		0.47				
not buzzing - buzzing			0.68			
not squeaking - squeaking			0.63			
jarring - dull		0.48	-0.61			
irregular - regular				-0.82		
monotone - varied				0.81		
single sound - mixture of sounds				0.67		
hollow - full					0.67	
not reverberant - reverberant					-0.58	
undamped - damped						
not noise-like - noise-like						0.71
slow - fast						0.60
explained variance:	20%	17%	8%	8%	5%	5%

Sub groups of fan sounds

A second PCA was conducted on the 36 sounds (based on all adjective ratings by all participants) to identify groups of sounds which were rated similarly. The KMO measure (KMO=0.94) and the Bartlett test ($\chi^2(630)=21027$, $p<0.01$) support the adequacy of the data set for a factor analysis. Based on the Kaiser criterion, five factors were extracted, shown in Table 2. It turns out that the first three factors (A, B and C) already cover more than 80% of the sounds (29 out of the overall 36 sounds). Each of the groups contain sounds from different types of fans (axial, radial and drum impeller) differing also in diameter ranges, rotation speeds and blade numbers. Apparently, technical parameters are only very weakly linked to the perceived sound characteristics for the broad range of fan sounds investigated in this study.

Table 2: Varimax rotated component matrix of the PCA conducted on the 36 sounds, indicating five groups of sounds: A, B, C, D and E. Factor loadings smaller than 0.4 were omitted for clarity reasons.

sounds	component				
	A	B	C	D	E
08-g	0.77				
11-f	0.76				
12-b	0.73				
12-r	0.71				
05-a	0.71				
07-b	0.65				
12-p	0.64				
08-a	0.64				
09-a	0.62				
11-e	0.60				
04-c	0.56				
02-c		0.75			
01-e		0.75			
13-c		0.75			
00-a		0.74			
06-b		0.64			
04-b		0.63			
01-a		0.62			
03-e		0.58			
03-d		0.55			0.42
00-c		0.50	0.46		
11-a		0.49	0.45		
02-a	0.42	0.45			
00-d		0.44			0.44
00-g		0.42			
03-c			0.80		
10-c			0.78		
00-f			0.77		
03-a			0.55	0.48	
13-a				0.57	
00-h2				0.56	
00-b				0.54	
07-c			0.50	0.51	
00-h1	0.47			0.51	
08-e	0.42				0.66
00-e					0.58
explained variance:	17%	15%	10%	8%	5%

Semantic profiles of the three major groups of sounds

For the interpretation of the groups of sounds which were identified by the second PCA, Figure 1 shows the mean sematic profiles of the three major groups. Even though all sounds were presented with the same A-weighted level, they differ considerably in the description of their sound character and also the rated pleasantness.

Sound group A was on average more unpleasant, disturbing, annoying, unbearable and obtrusive than the other two groups of sounds. Moreover, it was rated to be rather not humming, bassless, not booming and high on the second dimension II (“humming/bass”) and considerably more buzzing, squeaking and jarring than the other two groups on the third perceptual dimension III (“shrill”). This group is denoted “unpleasant”.

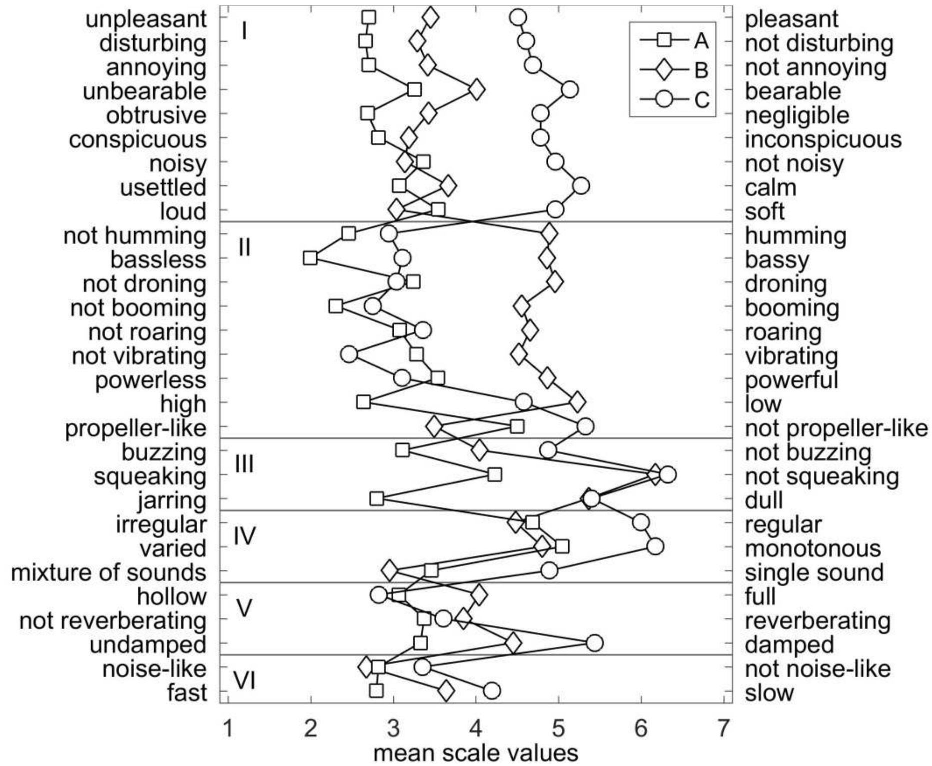

Figure 1: Semantic profiles of the three major groups of fan sounds. Mean ratings across the sounds of each of the three groups: A unpleasant sounds, B humming sounds and C pleasant sounds. The adjectives are ordered according to the identified perceptual dimensions which are separated by horizontal lines.

The average ratings over the sounds of group B are clearly more humming, bassy, droning, booming, roaring, vibrating, powerful, low and propeller-like on dimension II ("humming/bass") than the other two groups. Therefore, sound group B is characterized as "humming". With regard to the pleasantness, this group of sounds lies on average in between group A and group C.

The average of sound group C is clearly more pleasant than those from group A and B. The mean ratings with respect to each of the items loading to the first perceptual dimension I ("pleasant") are at least one scale unit higher for sound group C compared to the two other groups A and B. Furthermore, the sounds of this group are on average more regular, monotonous and single sound-like on the fourth dimension IV ("monotone") and more damped with regard to the fifth dimension V ("reverberant") than the two other groups of sounds. Sound group C is identified as "pleasant".

Specific loudness patterns of the three major groups of sounds

Figure 2 shows the average specific loudness pattern of the three major groups of sounds A, B and C, indicating systematic differences between the groups. The loudness was calculated based on a level of 55 dB(A) for each sound according to the German DIN 45631 standard and then averaged over the sounds of each group. On average, the sounds of group A ("unpleasant") have a very low amount of specific loudness below 2 Bark (~200 Hz) and a rather flat envelope up to 18 Bark (~4400 Hz). Above that, the specific loudness decreases towards 24 Bark (~15 kHz). The average curve for sound group B ("humming") shows considerably higher specific loudness up to 2 Bark (200 Hz) compared to the two other groups of sounds. For higher frequencies, the average curve is similar to that from sound group A ("unpleasant").

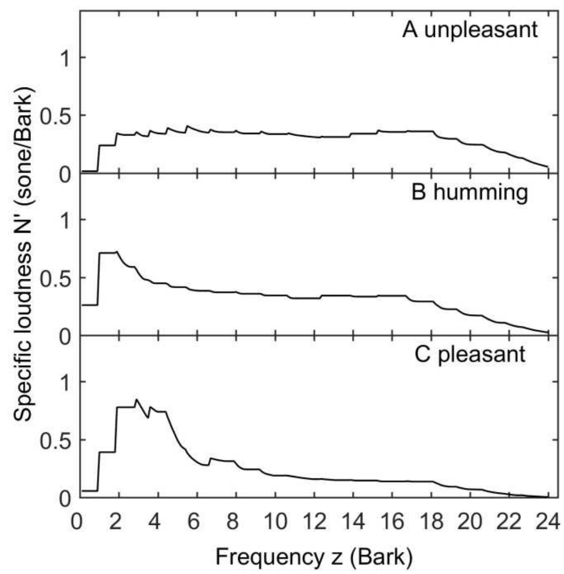

Figure 2: Mean specific loudness patterns of the three major groups of sounds: (A) unpleasant sounds, (B) humming sounds and (C) pleasant sounds

For sound group C ("pleasant"), the average specific loudness has a peak between 2 Bark (~200 Hz) and 5 Bark (~500 Hz). For higher frequencies above 10 Bark (~1300 Hz), the specific loudness is considerably lower for this group of sounds compared to group A ("unpleasant") and group B ("humming").

Given the systematic differences between the specific loudness patterns for the different groups of sounds, the specific loudness may be a basis to derive parameters which enable a better description of the identified three major perceptual dimensions of fan noise than current single values like e.g. the A-weighted sound pressure level or the psychoacoustic sharpness.

DISCUSSION

The factor analysis of the ratings for a broad variety of 35 fan sounds on 29 adjective scales revealed six perceptual dimensions: I pleasant, II humming/bass, III shrill, IV monotone, V reverberant and VI noise-like.

The perceptual dimensions identified in this study are in overall agreement with the five perceptual dimensions which were identified by Feldmann et al. [4] although the present stimulus set was considerably broader and the semantic differential was constructed based on adjectives provided by non-expert listeners in the present study. The first dimension I ("pleasant") with high loadings mainly from evaluative items is in good agreement with the first dimension from Feldmann et al. which they denoted "quality". The second dimension II ("humming/bass") is in overall agreement with the second dimension from the study of Feldmann et al. ("spectral content I") with high loadings of adjective scales like e.g. completely humming-not at all humming. Items form the third dimension III ("shrill") and the sixth dimension VI ("noise-like") fall together on the fifth dimension of Feldmann et al., denoted "spectral content II". The fourth dimension IV ("monotone") corresponds very well to the third dimension in the study of Feldmann et al. ("time structure"). The fourth dimension identified by Feldmann et al. ("power") falls onto the second dimension II ("humming/bass") of the present study with high loadings of the item powerless-powerful on this factor.

The adjective pairs used in the present semantic differential include most of the words that were also collected by Sung et al. for HVAC&R noises [5]. Only the acoustic aspect of impulsiveness which was a part of their collection of descriptive adjectives did not appear prominently for the fan sounds investigated here. Nevertheless, three out the four dimensions identified by Sung et al. for the HVAC&R sounds ("loudness", "tonal/sharpness", "irregular/fluctuation" and "not musical") are closely related to the perceptual dimension identified in the present study [6]. Their first dimension ("loudness") also contains high loadings of evaluative items like e.g. not acceptable and extremely annoying which corresponds to the first dimension I ("pleasant") of the present study. Their second and third factors closely resemble the third III ("shrill") and fourth dimension IV ("monotone") of this study. The last dimension from Sung et al. denoted "not musical" has no coincident factor in the present results because the aspect of musicality was not a part of the present semantic differential.

The found six perceptual dimensions of this study are also covering the three factors identified by Minard et al. for HVAC sound inside cars [7]. Their smaller set of 12 adjective scales might explain the smaller number of identified dimensions in their study.

Out of the five identified groups of sounds, the three major groups differ considerably in terms of their mean semantic profiles and the analysis of the specific loudness showed systematic differences between these three groups of sounds. Thus, regarding the overall objective, it might be possible to derive indexes based on the specific loudness which may correlate with the subjective judgments and enable an objective characterization of the most important perceptual dimensions. Such indexes might constitute a basis of a model for the characterization of the perceived pleasantness for fan sounds.

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