


**COVER PAGE**

***Document downloaded by @DAEL***

***Fri Nov 20 03:57:19 2026***
***For personal use***

When automatic English translation is provided, only the original document is authentic.
The EAA cannot be held responsible of any translation error

Bibliographical reference

*Perceptual Dimensions of Fan Noise and Their Relationship to Indexes Based On the Specific Loudness*, Stephan Töpken and Steven Van De Par, Acta Acustica **vol. 105** (Number 1), 2019, pp. 195-209

DOI
https://doi.org/10.3813/AAA.919300

**Acta Acustica united with Acustica**
**Vol. 105 (2019) 195 – 209**

DOI 10.3813/AAA.919300

# Perceptual Dimensions of Fan Noise and Their Relationship to Indexes Based On the Specific Loudness

Stephan Töpken, Steven van de Par
Acoustics Group, Department of Medical Physics and Acoustics, Carl von Ossietzky University, Carl-von-Ossietzky-Str. 9-11, 26129 Oldenburg, Germany. stephan.toepken@uni-oldenburg.de

**Summary**
Fan noise is a typical part of environmental noise perceived by humans in their daily life. In order to successfully develop more pleasant fan sounds, it is desirable to understand and characterize perceptually relevant aspects of fan noise beyond current technical measures like the dB(A). The aim of this study is a determination of the perceptual dimensions of fan noise, an identification of those dimensions which are relevant for the (un-)pleasantness and the development of (psycho-)acoustic indexes reflecting the most relevant perceptual dimensions. In a first experiment, a semantic differential was developed based on a free verbalization of adjectives and a rating of their suitability. In a second experiment, 35 different fan noises were rated by 45 participants using the developed semantic differential consisting of 29 adjective scales. As a result of a principal component analysis (PCA), six perceptual dimensions could be identified as "pleasant", "humming", "shrill", "monotone", "reverberant" and "noise-like". Another PCA revealed five groups of sounds which differed systematically in terms of their semantic profiles and calculated specific loudness. Based on an analysis of the specific loudness patterns of the signals, two new indexes were derived that differ systematically among three major groups of ventilator sounds comprising of unpleasant, humming and pleasant sounds.
**PACS no. 43.50.Qp, 43.66.Lj, 43.66.Cb, 43.66.Jh**

## 1. Introduction

Fan noise is a part of environmental noise that is perceived by humans in their daily life. In many cases the application of fans is technically indispensable for cooling purposes and the generation of sound can often not be avoided. In specific applications, sounds might even be associated with performance of a machine and therefore desirable in a specific context but in many use cases of fans the generated sound is an undesired by-product of the ventilation. For a successful development of more pleasant fan sounds, it is therefore necessary to better understand the rich variety of perceptual aspects related to fan sounds and to characterize especially those perceptual aspects which are linked to the appraisal of the sounds more appropriately than current technical measures like the A-weighted sound pressure level do [1].

The semantic differential is a common multi-dimensional method which enables a determination of the perceptual space of sounds by applying an exploratory factor analysis to multi-dimensional ratings of sounds [2]. In contrast to multi-dimensional scaling (MDS) techniques, which only rely on difference measures between objects (or sounds), an appropriate verbal space is required to comprehensively capture the perceptual dimensions with a semantic differential [3]. Different techniques based on free elicitation tasks have been used to collect specific verbal descriptors, e.g. for car interior sounds [4, 5]. In a recent study on fan noise, Feldmann *et al.* developed a semantic differential consisting of 37 adjective scales based on a free verbalization and a suitability assessment by twelve experts in acoustics [6]. In a further listening test of their study, 45 participants rated eight different fan sounds with the developed semantic differential. Based on a PCA, Feldmann *et al.* determined five perceptual dimensions underlying the data which were denoted "quality", "spectral content I", "temporal structure", "power" and "spectral content II". Sung *et al.* collected verbal descriptors for a broad variety of heating, ventilation, air conditioning and refrigeration (HVAC&R) noises [7]. Based on a factor analysis of ratings for nine original and thirteen modified recordings collected with a semantic differential consisting of 17 selected adjective scales, Sung *et al.* could identify four perceptual dimensions denoted "loudness", "tonal/sharpness", "irregular/fluctuation" and "not musical" [8]. For air-conditioning noise which mainly consists of the fan sound, Susini *et al.* identified three perceptual dimensions based on a multi- dimensional scaling of 19 sounds by 50 listeners [9]. The three identified dimen-

Received 22 December 2017,
accepted 1 November 2018.



*Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only*

sions correlated well with the noise-to-harmonic-energy-ratio based on the A-weighted signals, the spectral center of gravity of the noise component alone and the overall loudness of the sounds. Jeon and co-authors also investigated the acoustic comfort of indoor air conditioning sounds for a variation of the sound pressure level (SPL) in the frequency range of 250–630 Hz [10]. Based on a semantic differential consisting of 15 adjective scales, they identified two underlying factors, denoted refreshment and comfort. Minard *et al.* investigated the perceptual space of heating, ventilation and air conditioning (HVAC) sounds in cars with a semantic differential consisting of 12 adjective scales [11]. They identified three perceptual dimensions which were linked to the unpleasantness, sharpness and fluctuation of the sounds. In contrast to these three dimensions, they identified a combination of Moore's loudness model and the tonal audibility according to the ISO 1996-2 [12] as the best predictors for the unpleasantness judgments based on a stepwise regression approach.

In many cases, a close link was found between unpleasantness ratings and the psychoacoustic sharpness sensation or calculated sharpness values characterizing the amount of sound energy at very high frequencies [13, 14]. This includes fan noise itself [1] and also fan noise dominated products like HVAC sounds inside cars [15, 16] and inside trains [17], vacuum cleaners [18] and air cleaners [19]. Thus, models for the calculation of sharpness values like in the German DIN 45692 standard, which are based on the weighted sum of the specific loudness with an exponentially higher weight to frequencies above 15 Bark (2700 Hz), might be candidates for an index describing fan sounds [20].

The specific loudness was also used as a basis for the characterization of other sensations linked to the spectral content of sounds. Hatano and Hashimoto proposed an index based on third-octave levels to characterize the booming noise in cars. They determined the booming sensation for third-octave filtered pink noise centered at 25 Hz–800 Hz in listening tests and found a maximum sensitivity for the third-octave at 40 Hz. Therefore, they concentrated on the loudness below 280 Hz for the index and incorporated an exponentially increasing weighting function towards lower frequencies [21, 22]. Parizet *et al.* successfully employed a ratio of the loudness from different frequency regions for the description of the rather static broadband interior noise of high-speed trains [23]. They proposed a loudness balance between the loudness in the bands from 0–2 Bark and the loudness from 13–18 Bark to characterize the train interior noise which correlated very well with a preference ranking of the sounds [23]. Similarly, Alayrac *et al.* used a loudness difference in their regression models to predict annoyance from industrial sources [24]. Especially for noises with prominent spectral components in the middle frequency region, the inclusion of the loudness difference between the loudness in the range from 4 - 9 Bark and the range from 2 - 3 Bark contributed to the explained variance in their regression approach.

For an evaluation of sounds from air cleaners, Ih *et al.* divided the audible frequency range between low and mid frequencies at 400 Hz (4 Bark) and at 1250 Hz ($\approx$ 10 Bark) between mid and high frequencies [19]. Based on an annoyance metric they set up, they found a reduced annoyance for an increase of the low frequencies below 400 Hz by +6 dB combined with a reduction of the high or the high and mid frequencies by −6 dB. Similarly, Jeon *et al.* found that a modification of air conditioning noise by an increase of the sound pressure level in the frequency range of 250–630 Hz was beneficial in terms of the pleasantness for sounds with and also without prominent tonal components. In an analysis of the specific loudness of fan sounds, Schneider and Feldmann showed that the average loudness patterns can be quiet different between axial and radial fans [25]. Overall, all these studies suggest that an analysis of the specific loudness might be a promising approach for the characterization of fan sounds which in the end might also be linked to technical fan parameters.

The aims of this study are a determination of the perceptual dimensions for fan sounds, an identification of the major dimensions which are relevant for the (un-)pleasantness of fan sounds and to derive objective, (psycho-)acoustic indexes which enable a prediction of the most relevant perceptual dimensions. In the present study, a set of 35 fan sounds is investigated, including the eight sounds of Feldmann *et al.* [6], which aims at covering a rich variety of fan noise characteristics to obtain a rather general view on the perception of fan sounds. The sounds were delivered from overall eight manufacturers and one research institution, covering a broad range of different fan types.

In experiment 1 (Section 2), the verbal space for the fan sounds is explored and a semantic differential is developed based on two consecutive listening tests. The developed semantic differential is then used in experiment 2 (Section 3) to collect ratings of fan sounds. A two-fold factorial analysis is used to unveil perceptual dimensions and groups of sounds. An analysis of the specific loudness of the sounds in Section 4 shows distinct loudness patterns for the identified groups of sounds. Two new indexes, $N_{\text{ratio}}$ and $N_{\text{low}}$, are proposed for the characterization of fan noise based on the specific loudness. The results are eventually discussed in Section 5 and concluded in Section 6.

## 2. Experiment 1: Development of a semantic differential for fan noise

The aim of this first experiment is the development of a semantic differential for the characterization and evaluation of fan sounds.

### 2.1. Method of Experiment 1

Two consecutive listening tests were carried out to (i) collect adjectives for the description and evaluation of fan sounds and to (ii) assess the suitability of adjective pairs



Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only

compiled from the collected adjectives, in an approach similar to that from Chouard and Hempel [4] and Feldmann *et al.* [6].

#### 2.1.1. Procedure

Each of the two listening tests started by handing out written instructions to the participants and requesting written consent for a participation in the experiments. In a subsequent orientation phase, all sounds were played back in random order with a duration of 3 s each to familiarize the participants with the variety of sound characteristics embodied in the sounds.
(i) In the first listening test, the collection of adjectives consisted of two description phases. In both phases, the task for the participants was to write down any terms to describe and to evaluate fan sounds that would come to their minds and to note all similarities and differences between sounds or groups of sounds. In addition, the participants were also asked for situations, sounds sources and associations linked to fan sounds, mainly to promote their creativity. After having completed the first description phase with a random sequence of all sounds, all forms were collected from the participants and new forms were distributed for the second description phase. Both description phases were carried out in exactly the same way to provide the participants with two possibilities to fully collect all perceptual aspects they became aware of.
(ii) In the second listening test, the task for the participants was to assess each of 106 adjective pairs which were compiled based on the results of the first listening test in terms of its suitability to describe or evaluate the entity of all different fan sounds. The assessment of the adjective pairs took place on a categorial five point rating scale from 1 (not at all suitable) to 5 (very suitable). The adjective pairs and the rating scales were printed under each other on overall six DIN A4 pages.

At the end of each of the two listening tests, a short questionnaire and a compensation completed each session. The two listening tests were separated by about 4 weeks.

#### 2.1.2. Participants

Both listening tests were carried out with paid volunteer students from the University of Oldenburg. In contrast to the study of Feldmann *et al.* [6], they can not be considered as being acoustic experts.
(i) Overall, 33 volunteers (21 female, 12 male) participated in the collection of the adjectives. The mean age of the participants was 24 years with a minimum of 20 years and a maximum of 30 years. About 45% of the participants (15/33 participants) were not experienced with listening test in general. The other 55% (18/33 participants) already participated in other listening tests before.
(ii) Overall, 31 participants (20 female, 11 male) which already participated in the collection of the adjectives took part in the suitability assessments. Two of the former participants from the collection of the adjectives did not participate in this second listening test. The mean age of the participants and the percentage of experience with listening tests was essentially the same as in the first listening test (i). All participants stated that they were normal hearing.

#### 2.1.3. Apparatus

The listening setup was the same for the collection of adjectives (i) and the assessment of their suitability (ii). In both cases, the listening experiments were carried out as group experiments with up to 4 participants at the same time. The participants sat on one side of a hexagonal table with a diameter of 2.8 m in a seminar room ($T_{60}$ = 0.4 s). The fan sounds were presented over a loudspeaker (Mackie, HR 824 Mk 2) which was positioned about 2.3 m in front of the participants. The loudspeaker was driven by an external audio interface (RME, Fireface UCX). The randomized playback of the signals was prepared in MATLAB (The Mathworks).

#### 2.1.4. Stimuli

Overall 57 different fan sounds were used as stimuli in the listening tests. The signals were microphone recordings from 21 axial fans, 33 radial fans and 3 drum impellers, covering a broad range of fan diameters (77–2818 mm), rotation speeds (550–4481 rpm) and blade numbers (5–59 blades). All sounds were equalized to the same A-weighted sound pressure level of 60 dB(A) to minimize prominent loudness differences [26] and re-sampled to a common sampling rate of 44100 Hz.
(i) For the collection of the adjectives, the signals were played back with a duration of 25 s, each. This rather long duration was chosen to enable the participants to fully listen into the sounds. Each sound was presented only once, separated by a pause of about 0.5 s from the successive sound. The order of the sounds was randomized. The duration of one complete sequence of all 57 sounds was about 25 minutes.
(ii) For the suitability assessments, the signals were played back with a duration of 5 s, each. All sounds were presented in a random order and separated by a pause of about 0.5 s. The randomized playback continued until all assessment of all participants of a group listening test were collected. The duration of 5 s was chosen so that the participants could listen to several successive sounds for the suitability rating of each of the adjective pairs.

### 2.2. Results of Experiment 1

#### 2.2.1. Collection of adjectives (i)

The free verbalization of the first listening test led to a collection of overall 438 different adjectives. Semantically close adjectives were summarized under umbrella terms, e.g. the attributes 1x *unbearable*, 2x *not bearable*, 2x *unendurable*, 2x *bearable*, 2x *endurable*, 2x *tolerable* were collected as the adjective pair *unbearable - bearable* with a total count of eleven. The number of occurrences were counted over the two verbalization runs whereas a count of two was the maximum for each item per participant. In this way, a bias due to multiple repeated responses by single participants could be prevented. Nevertheless, the inclusion of the responses of each of the two rounds into the



Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only

counting allowed for a higher weighting of items that were stated in the first and in the second description phase and not just once. A selection criterion of at least 3 occurrences was chosen, to make sure that an item was stated by at least two different participants. Based on this criterion, adjectives were selected and 106 different adjective pairs (53 uni-polar and 53 bi-polar) were constructed which were then the basis for a suitability assessment in the successive second listening test (ii).

#### 2.2.2. Suitability assessment (ii)

In the second listening test, the suitability of the adjective pairs to characterize the fan sounds were rated on a 5 point categorial scale from 1 (not suitable at all) to 5 (very suitable). The median ratings over all 31 participants were the basis of the selection. To chose only suitable adjective pairs, the criterion was set to a median rating of at least four. Applying this criterion, 24 adjective pairs were selected for the semantic differential. Five additional adjective scales (No. 25-29 in Table I) were chosen to complement the list. They cover the aspects of regularity, speed and powerfulness which were part of the study of Feldmann *et al.* [27]. Table I shows the complete semantic differential consisting of overall 29 adjective pairs as English translations and the originally used German versions. It is worth noting that the evaluative German term *lärmend* which is semantically close to the German adjective *lärmhaft* was translated as *noisy*. In contrast to that, the rather neutral description of a noise signal, which is *rauschhaft* in German, was translated by *noise-like* [28].

Table I. English translations of the 29 adjective scales from the semantic differential. The originally used scales in German language are given in brackets below each English adjective pair.

| No. | adjective scale | | |
|---|---|---|---|
| 1 | soft | – | loud |
| | (leise | – | laut) |
| 2 | low | – | high |
| | (tief | – | hoch) |
| 3 | unpleasant | – | pleasant |
| | (unangenehm | – | angenehm) |
| 4 | not noise-like | – | noise-like |
| | (nicht rauschend | – | rauschend) |
| 5 | jarring | – | dull |
| | (schrill | – | dumpf) |
| 6 | not disturbing | – | disturbing |
| | (nicht störend | – | störend) |
| 7 | not droning | – | droning |
| | (nicht dröhnend | – | dröhnend) |
| 8 | not humming | – | humming |
| | (nicht brummend | – | brummend) |
| 9 | not annoying | – | annoying |
| | (nicht nervig | – | nervig) |
| 10 | not vibrating | – | vibrating |
| | (nicht vibrierend | – | vibrierend) |
| 11 | bassless | – | bassy |
| | (basslos | – | bassig) |
| 12 | agitated | – | calm |
| | (unruhig | – | ruhig) |
| 13 | not buzzing | – | buzzing |
| | (nicht surrend | – | surrend) |
| 14 | unbearable | – | bearable |
| | (unerträglich | – | erträglich) |
| 15 | not reverberating | – | reverberating |
| | (nicht hallend | – | hallend) |
| 16 | single sound | – | mixture of sounds |
| | (Einzelgeräusch | – | Geräuschgemisch) |
| 17 | obtrusive | – | negligible |
| | (penetrant | – | ausblendbar) |
| 18 | not roaring | – | roaring |
| | (nicht röhrend | – | röhrend) |
| 19 | inconspicuous | – | conspicuous |
| | (unauffällig | – | auffällig) |
| 20 | not squeaking | – | squeaking |
| | (nicht fiepend | – | fiepend) |
| 21 | undamped | – | damped |
| | (ungedämpft | – | gedämpft) |
| 22 | not noisy | – | noisy |
| | (nicht lärmend | – | lärmend) |
| 23 | not propeller-like | – | propeller-like |
| | (nicht propellerartig | – | propellerartig) |
| 24 | not booming | – | booming |
| | (nicht wummernd | – | wumernd) |
| 25 | monotonous | – | varied |
| | (monoton | – | abwechslungsreich) |
| 26 | irregular | – | regular |
| | (ungleichmäSSig | – | gleichmäSSig) |
| 27 | slow | – | fast |
| | (langsam | – | schnell) |
| 28 | powerless | – | powerful |
| | (kraftlos | – | kräftig) |
| 29 | hollow | – | full |
| | (hohl | – | voll) |

## 3. Experiment 2: Dimensions of the perceptual space for fan noise

The aim of this second experiment is the characterization of the perceptual space for 35 fan sounds with the semantic differential developed in experiment 1 and the identification of those perceptual dimensions which are most important for the (un-)pleasantness of the fan sounds.

### 3.1. Method of Experiment 2

#### 3.1.1. Procedure

The listening tests were carried out as single participant experiments in two distinct sessions separated by at least one week. Each session started by giving some general information about the listening experiment and handing out written instructions to the participant. In the first session also written consent was collected from the participant. In an orientation phase, each participant was familiarized with all 35 sounds and by reading all 29 adjective scales. The participants were informed that the aim of the study was an assessment of different fan sounds which may occur in the context of everyday life. After the orientation phase, one of two sets of sounds consisting of 18 sounds (out of a total of 36 sounds including one repetition) was rated on all 29 adjective scales. Table I presents English translations and the originally used German adjective scales of the semantic differential. The 16 bipolar and 13 unipolar adjective pairs marked the ends of a seven



Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only

point categorial scale, each. Each of the sounds was played back repeatedly until the ratings for all 29 adjective scales were completed. Only then the next sound was presented. The order of the adjective scales for each sound and the presentation order of the 18 sounds was randomized individually for each participant to reduce order effects. After completing all ratings, a short questionnaire and interview was carried out with the participant to obtain additional qualitative insight into the ratings. The questionnaire included a question on the criteria used by the participants for the evaluation of the fan sounds and also a question whether an adjective was missing in the semantic differential. At the end of the second session, the participant also filled out a form for the compensation. Each session had a duration of maximally 90 minutes while the listening test itself took between 35 and 60 minutes.

#### 3.1.2. Participants

Overall 45 persons (23 female, 22 male) participated in the listening tests. They were mainly students and employees from the University of Oldenburg. The mean age of the participants was 25 years (from 18 to 48 years). About 56% of the participants (15 female, 10 male) were not experienced with listening tests in general. The other 44% (8 female, 12 male) already participated in other listening tests before. None of the 45 listeners from experiment 2 already participated in experiment 1.

#### 3.1.3. Apparatus

The listening tests took place in a double-walled sound proof booth. The background noise level inside the booth was in the range of the lower limit of a handheld sound level meter (Norsonic, Nor 140) of 17 dB(A). The fan sounds were presented diotically via headphones (Sennheiser, HD 650). The headphones were driven by the headphone output of an external audio interface (RME, Fireface UCX) which was connected to a computer. The experimental procedure for the collection of the ratings was implemented in MATLAB (The Mathworks) with a graphical user interface presenting the scales while the sounds were played back. The presentation level of the sounds was calibrated using an artificial ear (B&K, Type 4153) with a 1/2" microphone capsule (B&K, Type 4134) and a measurement amplifier (B&K, Type 2610). The calibration was checked by an electrical measurement of the voltage at the headphone output on each day. In addition to the electrical checks, the calibration was also checked with the artificial ear on two days, one near the middle and one towards the end of the measurement campaign.

#### 3.1.4. Stimuli

Overall 35 different fan sounds were rated in experiment 2 which were a subset of the 57 sounds from experiment 1. Redundant signals which sounded very similar and had either the same or very similar technical specifications were taken out by the experimenter. This selection was carried out in close cooperation with experts from the fan manufactures that provided the sound samples. The 35 signals were microphone recordings from 13 axial fans, 20 radial fans and 2 drum impellers, covering a broad range of fan diameters (146–2818 mm), rotation speeds (624–4481 rpm) and blade numbers (5–59 blades). The signals were delivered by 8 different manufacturers and the University of Siegen (Germany). In one case, the recordings were carried out by the University of Oldenburg at a manufacturer site.

The 35 fan sounds were divided into two sets of sounds to reduce the duration of a listening experiment session reasonably. One signal (#08) was measured repeatedly as a part of the first sound set (#08-1) and the second sound set (#08-2) to allow for an assessment of the test-retest reliability, resulting in 18 sounds for each of the two sound sets and overall 36 sounds. The two sets were balanced sonically and also in terms of fan types represented in each set. Due to the rich variety of sound characteristics, it was very difficult to define objective decision criteria based on technical specifications. Definite perceptual criteria were not available at this point of the study because it was the ultimate goal of the study to unveil the dimensions underlying the perception of fan noise. Therefore, the two groups of sounds were compiled by the experimenter in a subjective decision which was verified by two acoustic experts from our working group. Although the particular sounds were different in the two sets despite one single repeated sound, both experts could confirm that no striking differences between the two groups were obvious and that the broad variety of different sound characteristics was rather evenly distributed over both sets. Comments from the participants at the end of the second session, after having rated both sets of sounds, indicate that the two sets were not perceived as being very different. For some participants the two sets even were completely identical. For other participants, only single prominent sounds were missing or a new sound was salient while the rest of the sounds was the same for them. This feedback from the participants suggests that the sonic balance between the two groups of sounds was effectively achieved in general.

The duration of the stimuli was 5 seconds, each. In the listening experiments, each stimulus was presented repeatedly with a short break of half a second until the ratings for all 29 adjective scales were collected. All sounds were presented with the same fixed sound pressure level of 55 dB(A) to minimize the influence of prominent loudness differences between the sounds on the characterization and evaluation [26].

### 3.2. Results of Experiment 2

An analysis of the reliability of the repeatedly measured signal #08 is presented in Section 3.2.1. The ratings of the 45 participants on 29 adjective scales for the 36 sounds were used as the raw data for two exploratory factor analyses. One principal component analysis (PCA) was carried out on the 29 adjective scales (defined by the ratings of all sounds by all participants) to identify the latent dimensions of the perceptual space (Section 3.2.2). Another PCA was conducted on the 36 sounds (defined by the ratings of all participants on all adjective scales)



Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only

to identify groups of sounds which were judged similarly (Section 3.2.3). Semantic profiles of the sound groups on the identified perceptual dimensions (Section 3.2.4) allow for a characterization of the groups of sounds and indicate which of the perceptual aspects were most relevant for the evaluation of the sounds. A qualitative analysis of the answers from the interview at the end of the second session gives insight into the evaluation criteria used by the participants which further support an analysis of the specific loudness of the sounds (Section 3.2.5).

### 3.2.1. Reliability of the ratings

One signal (#08) was measured repeatedly as a part of both sound sets. Figure 1 (left) shows the mean ratings of signal #08 as a part of the two sound sets for all adjective scales. The correlation coefficient between the mean judgments across all participants from sound set 1 and sound set 2 is calculated to evaluate the influence of the acoustic context created by the other sounds in set 1 and set 2. The correlation coefficient between the mean judgments across participants for signal #08 in the context of set 1 and set 2 is $r = 0.916$ ($p < 0.001$). This means that the context created by the two sound sets did not substantially influence the ratings. In addition, it was evaluated whether the repeated rating of sound #08 either as a part of set 1 or 2 had an influence. About half of the participants started with sound set 1 and the other half with sound set 2. After individually resorting the raw data in terms of the first rating (test) and repeated rating (retest), a correlation coefficient of $r = 0.918$ ($p < 0.001$) is obtained between the mean test and retest ratings (shown in Figure 1, right). Overall, these results suggests high reproducibility of the results in the context of the two sets of sounds as well as in terms of the test-retest condition.

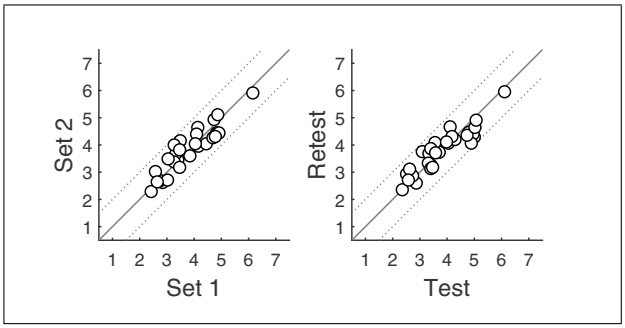



Figure 1. Mean ratings of signal #08 measured across participants for all adjective scales as a part of the two sound sets (left) and individually resorted into test and retest condition (right). The straight diagonal lines indicate perfect agreement and dashed lines indicate a range of plus/minus one scale unit.

### 3.2.2. Dimensions of the perceptual space

The individual ratings of all 29 adjective scales by all 45 participants for all 36 sounds were the raw data used for an exploratory factor analysis to determine the dimensions of the perceptual space. The Kaiser-Meyer-Olkin (KMO) measure of sample adequacy ($KMO = 0.92$, "superb" according to Field [29]) and the Bartlett test of sphericity ($\chi^2(406) = 23035,\ p < 0.01$) prove the adequacy of the data set for a factor analysis. Based on the Kaiser criterion, six factors were extracted which together explain 62% of the variance. The scree plot showed inflections that would also justify the extraction of only three or five factors, but given the large number of items, the sample size and the good interpretability, we decided to retain the identified six factors. The Varimax-rotated component matrix is given in Table II. Following the suggestion from Stevens, factor loadings larger than 0.4 are used for the interpretation of the factors given the size of the data set [30].

The first factor I, explaining 20% of the variance, can be regarded as the "pleasant" dimension with high loadings of the adjective scales *unpleasant - pleasant*, *not disturbing - disturbing*, *not annoying - annoying*, *unbearable - bearable*, *obtrusive - negligible*, *inconspicuous - conspicuous*, *not noisy - noisy*, *agitated - calm* and *soft - loud*. The second factor II, explaining 17% of the variance, shows high loadings of the adjective scales *not humming - humming*, *bassless - bassy*, *not droning - droning*, *not booming - booming*, *not roaring - roaring*, *not vibrating - vibrating*, *powerless - powerful*, *low - high*, *not propeller-like - propeller-like*. This perceptual dimension can be interpreted as "humming/bass". The third factor III represents the "shrillness" of the sounds with high loadings of the scales *not buzzing - buzzing*, *not squeaking - squeaking* and *jarring - dull*, explaining 8% of the variance. The fourth factor IV covers temporal aspects of the sounds with high loadings of the adjective scales *irregular - regular*, *monotone - varied* and *single sound - mixture of sounds*, explaining 8% of the variance. It was denoted "monotone". The fifth factor V describes the "reverberance" of the sounds with high loadings from the scales *hollow - full* and *not reverberant - reverberant*. The sixth factor VI brings together the scales *not noise-like - noise-like* and *slow - fast*. These last two factors explain another 5% of the variance, each.

The results show that the five additionally added items contributed in parts to the explained variance and could be meaningfully used by the participants to characterize the fan sounds. The item *powerless - powerful* has a high positive loading on the second dimension (humming/bass). Thus, sounds that are humming and rather bassy are connoted with being powerful whereas sounds which are not humming and bassless have a connotation of being powerless. The items *irregular - regular*, *monotone - varied* formed the fourth dimension together with the item *single sound - mixture of sounds*. The factor loadings indicate that sounds, which are irregular and varied, are also perceived as a mixture of sounds and single sounds were described as rather monotone and regular. Thus, these items allowed a complementing characterization of the fan sounds in terms of their temporal variation, even if they did not reach the selection criterion in the suitability assessment in Section 2.2.2. The items *hollow - full* and *slow - fast* together with some other items are found on the last two factors which explained only little variance in the data.



*Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only*

Table II. Results of the PCA on the 29 adjective scales (varimax-rotated component matrix with factor loadings/correlation coefficients) showing six perceptual dimensions which can be interpreted as I pleasant, II humming/bass, III shrill, IV monotone, V reverberant and VI noise-like. Factor loadings ≤ 0.4 are omitted for clarity reasons.

| perceptual dimension | adjective scales | component I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|---|
| I pleasant | 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 | | | | | |
| II humming/bass | 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 | | | | |
| III shrill | not buzzing - buzzing | | | 0.68 | | | |
| | not squeaking - squeaking | | | 0.63 | | | |
| | jarring - dull | | 0.48 | -0.61 | | | |
| IV monotone | irregular - regular | | | | -0.82 | | |
| | monotone - varied | | | | 0.81 | | |
| | single sound - mixture of sounds | | | | 0.67 | | |
| V reverberant | hollow - full | | | | | 0.67 | |
| | not reverberant - reverberant | | | | | -0.58 | |
| | undamped - damped | | | | | | |
| VI noise-like | not noise-like - noise-like | | | | | | 0.71 |
| | slow - fast | | | | | | 0.60 |
| | explained variance: | 20% | 17% | 8% | 8% | 5% | 5% |

### 3.2.3. Grouping of the sounds

The individual ratings of all 36 sounds on all 29 adjective scales by all 45 participants were the raw data used for a second exploratory factor analysis to determine groups of sounds which were judged similarly. The Kaiser-Meyer-Olkin (KMO) measure of sample adequacy ($KMO = 0.94$, "superb" according to Field [29]) and the Bartlett test of sphericity ($\chi^2(630) = 21027,\ p < 0.01$) prove the adequacy of the data set for a factor analysis. Based on the Kaiser criterion, five factors A–E were extracted which together explain 55% of the variance. Table III shows the Varimax-rotated component matrix.

Most of the sounds are already covered by the first two factors. Factor A has high loadings of 11 sounds, explaining 17% of the variance and factor B has high loadings of 14 sound explaining 15% of the variance. The other three factors have high loadings of four (C), five (D) and two (E) sounds which together explain 23% of the variance. The first three factors comprise already 80% of the sounds which account for 42% of the variance in the data. The scree plot showed inflections that would also justify the extraction of only four factors. In this alternative solution, the two sounds from the present fifth factor E would fall onto the first factor A, while the interpretation for the four factors would remain the same like for the factors A-D of the five factor solution. The repeated measurement of sound #08-2 is found on the same factor as the initial judgment #08-1. This further supports the reliability of the ratings for this sound which was judged very similar as a part of each of the two sound sets.

### 3.2.4. Mean semantic profiles of the sound sub-groups

In order to characterize the groups of sounds identified as factors of the second PCA, Figure 2 shows the semantic profiles of the mean ratings for all five groups of sounds, averaged across the sounds of each group. The distinct profiles suggest that the five groups of sounds were perceived considerably different. In the following the specific characteristics of each group compared to the other groups of sounds are described. Sound group A, consisting of



Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only

Table III. Results of the PCA on the 36 sounds (varimax-rotated component matrix with factor loadings/correlation coefficients) showing five groups of sounds: A, B, C, D and E. Factor loadings ≤ 0.4 are omitted for clarity reasons.

| sound group | sound | component A | B | C | D | E |
|---|---|---|---|---|---|---|
| A | #25 | 0.77 | | | | |
| unpleasant | #30 | 0.76 | | | | |
| | #31 | 0.73 | | | | |
| | #33 | 0.71 | | | | |
| | #19 | 0.71 | | | | |
| | #21 | 0.65 | | | | |
| | #32 | 0.64 | | | | |
| | #23 | 0.64 | | | | |
| | #26 | 0.62 | | | | |
| | #29 | 0.60 | | | | |
| | #18 | 0.56 | | | | |
| B | #12 | | 0.75 | | | |
| humming | #10 | | 0.75 | | | |
| | #35 | | 0.75 | | | |
| | #01 | | 0.74 | | | |
| | #20 | | 0.64 | | | |
| | #17 | | 0.63 | | | |
| | #09 | | 0.62 | | | |
| | #16 | | 0.58 | | | |
| | #15 | | 0.55 | | | 0.42 |
| | #03 | | 0.50 | 0.46 | | |
| | #28 | | 0.49 | 0.45 | | |
| | #11 | 0.42 | 0.45 | | | |
| | #04 | | 0.44 | | | 0.44 |
| | #07 | | 0.42 | | | |
| C | #14 | | | 0.80 | | |
| pleasant | #27 | | | 0.78 | | |
| | #06 | | | 0.77 | | |
| | #13 | | | 0.55 | 0.48 | |
| D | #34 | | | | 0.57 | |
| noise-like | #08-2 | | | | 0.56 | |
| | #02 | | | | 0.54 | |
| | #22 | | | 0.50 | 0.51 | |
| | #08-1 | 0.47 | | | 0.51 | |
| E | #24 | 0.42 | | | | 0.66 |
| varied | #05 | | | | | 0.58 |
| explained variance: | | 17% | 15% | 10% | 8% | 5% |

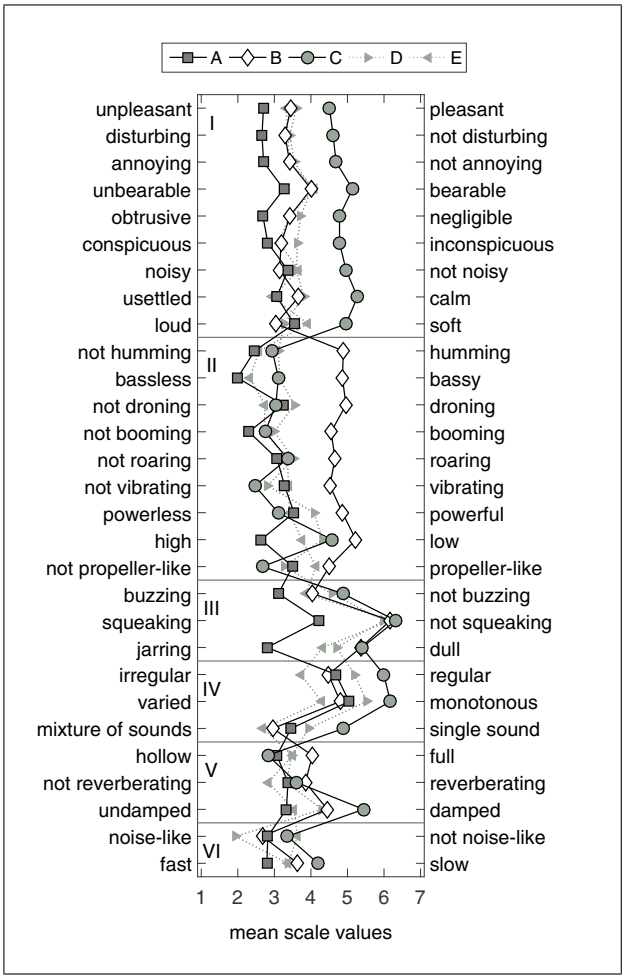



Figure 2. Semantic profiles based on the mean ratings of the five sound groups (A-E, identified by the different symbols) from the PCA (see Table III). Roman numerals indicate the six perceptual dimensions (I-VI) from Table II which are separated by horizontal lines.

11 sounds, is clearly more unpleasant, disturbing, annoying, unbearable, obtrusive and conspicuous on the first dimension I (pleasant) than all other groups. Therefore, this group of sounds is characterized as unpleasant. In addition it is also not humming, bassless, not booming and high on the second perceptual dimension II (humming/bass) and it is buzzing, squeaking and jarring on the third dimension III (shrill) compared to the other groups, each.

Sound group B, consisting of 14 sounds, is judged rather neutral on the evaluative first dimension I (pleasant), but compared to all other groups it is clearly humming, bassy, droning, booming, roaring, vibrating, powerful, low and propeller-like on the second dimension II (humming/bass). Therefore, this group of sounds is labeled humming.

In relation to the other groups of sounds, Sound group C, consisting of four sounds, is clearly pleasant, not disturbing, not annoying, bearable, negligible, inconspicuous, not noisy, calm and soft on the first dimension I (pleasant). Thus, it is labeled pleasant. Furthermore, this group is not propeller-like on the second dimension II (humming/bass), regular, monotonous and rather a single sound on dimension IV (monotone) and damped on dimension V (reverberant).

Sound group D, consisting of five sounds including one repetition, is in the middle compared to the other groups of sounds with respect to most adjective scales, but it is judged to be the most noise-like group of sounds on dimension VI (noise-like), hence the label noise-like. Sound group E, consisting of only two sounds, is also evaluated rather neutrally and it is characterized as more irregular, more varied and rather a mixture of sounds compared to the other groups on dimension IV (monotone). It is labeled varied.



*Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only*

#### 3.2.5. Evaluation criteria and completeness of the semantic differential

In addition to the quantitative data in terms of the ratings with the semantic differential, also a short interview was carried out with each participant. One of the questions in the interview at the end of the second session asked for the evaluation criteria which were adduced by the participants when evaluating the fan sounds in terms of the pleasantness. The stated criteria are in overall agreement with the assessment of the sounds in the semantic differential. In general, the participants found the damped, humming, monotonous and low frequency sounds more pleasant than the squeaking, shrill, irregular and high sounds which were rather unpleasant. In addition, ten out of the 45 participants (22%) further refined their statements. They explicitly mentioned that if the sounds were too low, too booming, too dull or with too much bass, then the sounds were also unpleasant for them. Hence, a certain spectral balance between mid frequency and high frequency content was preferred by these participants and too much content at very low frequencies was rather detrimental for them. In particular, this finding suggests that a separate consideration of high and very low frequencies in separate indexes might be useful for an appropriate description of fan sounds which is further followed in Section 4.2.

Although considerable effort went into the identification and selection of the adjective pairs, it might have been possible that some perceptual aspects were not sufficiently covered by the developed semantic differential and that the set of adjectives might have been incomplete [5]. Therefore, the participants were asked in the interview at the end of the second session, whether an adjective was missing for them. For 37 participants (82%) this was not the case. Only eight out of the 45 participants stated the following items as missing (followed by the German translation): *tinny* (2x blechern), *known from everyday life* (aus dem Alltag bekannt), *motor sound instead of propeller sound* (Motorgeräusch anstatt Propellergeräusch), *puffing* (pustend), *blowing* (blasend), *fluttering* (flatternd), *whistling* (2x pfeifend). Apart from *known from everyday life* and *motor sound*, all stated items were part of the collection of 438 adjectives in the first listening test of experiment 1(i). Therefore, it is not surprising that they were stated as missing by a few of the participants. Nevertheless, these adjectives have been discarded in the selection process for the semantic differential based on the suitability assessments in the second listening test of experiment 1(ii). The low number of missing adjectives stated by only 18% of the participants suggests that the semantic differential was generally complete and covered the most relevant perceptual aspects for the vast majority of the participants.

## 4. Indexes based on the specific loudness

An analysis of the specific loudness patterns of the fan sounds is presented in Section 4.1. Based on the specific loudness, two new indexes were derived (Section 4.2) which enable a distinction between the identified major groups of sounds and which have a close link to the most important perceptual dimensions (Section 4.3).

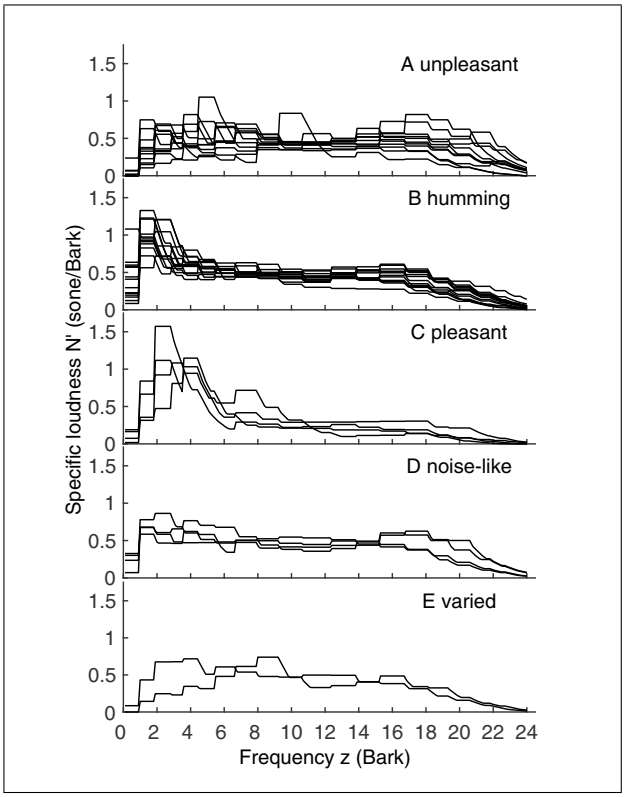



Figure 3. Specific loudness $N'$ plotted over the frequency $z$ in Bark for the all sounds sorted according to the five groups of sounds (A-E) identified by the PCA (Table III).

### 4.1. Analysis of the specific loudness for the five identified groups of sounds

The specific loudness of all 35 fan sounds calculated by the DIN 45631 standard [31] is shown in Figure 3. The calculation is based on an implementation of the ISO 532 B by Genesis Acoustics[1], which equals the German DIN 45631 standard [32, 33].

The unpleasant sounds from sound group A show a considerably higher specific loudness for frequencies above 10 Bark than the sounds of all other sound groups. In contrast to this, the group of pleasant sounds C has very low values of the specific loudness above 10 Bark, but a considerable amount of specific loudness in the range of 2 - 5 Bark. The group of the humming sounds B has a very high amount of specific loudness in the range of 0 - 3 Bark. These identified frequency ranges will be used in the definition of indexes in Section 4.2. Sound group D (noise-like) and E (varied) have very little low frequency content compared to the humming B and pleasant C sounds and a rather flat shape of the specific loudness for frequencies above that.

[1] http://genesis-acoustics.com/en/loudness_online-32.html, accessed: July 2017



Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only

### 4.2. Definition of two indexes based on the specific loudness: $N_{\text{ratio}}$ and $N_{\text{low}}$

Based on the the distinct semantic profiles of the groups of sounds (Section 3.2.4), the evaluation criteria stated in the interviews (Section 3.2.5) and the analysis of the specific loudness (Section 4.1), we propose two indexes to characterize the different groups of sounds and the unpleasantness of the fan sounds. The two new indexes are each based on a ratio between weighted sums of the specific loudness. The weighting functions are displayed in Figure 4.

The first proposed index $N_{\text{ratio}}$ puts the loudness from about 2 Bark to 5 Bark in relation to the loudness from 10 Bark to 24 Bark with a broad overlap in between these two frequency regions. The index is intended to distinguish between the sound group A (unpleasant) and sound group C (pleasant) and it is defined as:

$$N_{\text{ratio}} = \frac{\int_{0\ Bark}^{24\ Bark} w_1(z) \cdot N'(z)\ \mathrm{d}z}{\int_{0\ Bark}^{24\ Bark} w_2(z) \cdot N'(z)\ \mathrm{d}z} \tag{1}$$

with the two weighting functions $w_1$ and $w_2$ defined by

$$w_1(z) = \begin{cases} 0 & z = 0 \ldots 1.5\ \text{Bark} \\ z - 1.5 & z = 1.5 \ldots 2.5\ \text{Bark} \\ 1 & z = 2.5 \ldots 5\ \text{Bark} \\ -0.2 \cdot z + 2 & z = 5 \ldots 10\ \text{Bark} \\ 0 & z = 10 \ldots 24\ \text{Bark} \end{cases} \tag{2}$$

and

$$w_2(z) = \begin{cases} 0 & z = 0 \ldots 5\ \text{Bark} \\ 0.2 \cdot z - 1 & z = 5 \ldots 10\ \text{Bark} \\ 1 & z = 10 \ldots 24\ \text{Bark} \end{cases} \tag{3}$$

The second index $N_{\text{low}}$ normalizes the loudness from 0 Bark to 2 Bark by the overall loudness $N$ of the sound which is equal to the integration of the specific loudness $N'$ over the whole frequency range from 0 Bark to 24 Bark. It is intended to distinguish the sound group B (humming) with a lot of low frequency content from the other groups of sounds and it is defined as

$$N_{\text{low}} = \frac{\int_{0\ Bark}^{24\ Bark} w_0(z) \cdot N'(z)\ \mathrm{d}z}{\int_{0\ Bark}^{24\ Bark} N'(z)\ \mathrm{d}z} \tag{4}$$

with the weighting function $w_0$ defined as

$$w_0(z) = \begin{cases} 1 & z = 0 \ldots 1.5\ \text{Bark} \\ -z + 2.5 & z = 1.5 \ldots 2.5\ \text{Bark} \\ 0 & z = 2.5 \ldots 24\ \text{Bark} \end{cases} \tag{5}$$

Figure 5 shows the relationship between the values of the two indexes $N_{\text{ratio}}$ and $N_{\text{low}}$. In this representation, the group of unpleasant sounds A (square symbols in Figure 5) is found in the lower left corner with rather low values for $N_{\text{ratio}}$ and also for $N_{\text{low}}$. The group of the humming sounds B (diamond symbols in Figure 5) is found in the upper left corner with low values for $N_{\text{ratio}}$ and rather high values for $N_{\text{low}}$. The group of pleasant sounds C (circles in Figure 5) is located on the right side of the figure with values of $N_{\text{ratio}} \geq 1$, separated from all other sounds.

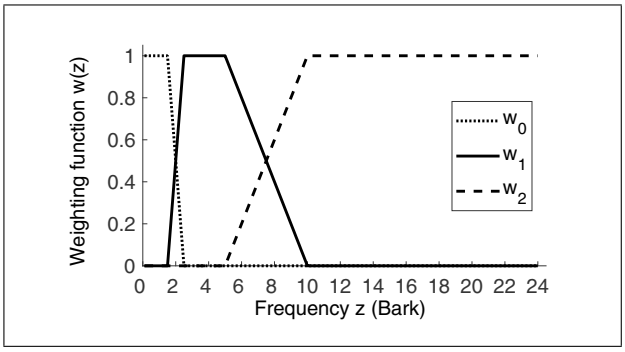



Figure 4. Weighting functions $w_0$ used for the index $N_{\text{low}}$ and $w_1$ and $w_2$ used for $N_{\text{ratio}}$, defined by linear factors $w(z)$ as a function of the frequency $z$ in Bark.

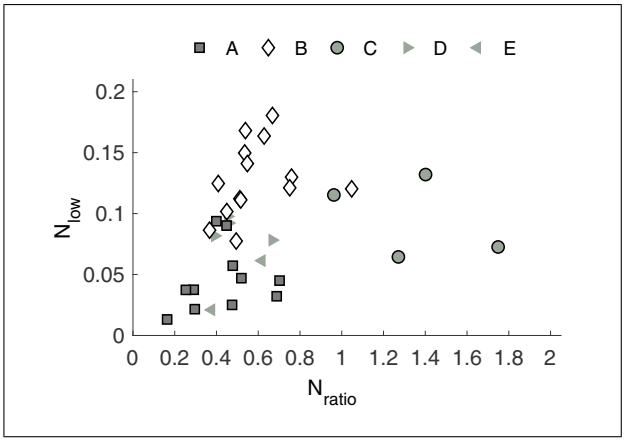



Figure 5. Scatter plot of the values from the two proposed indexes $N_{\text{ratio}}$ and $N_{\text{low}}$ for the 35 investigated fan signals. The five groups of sounds A to E (identified by the second PCA, Table III) are indicated by the symbols. The two indexes effectively differentiate between the unpleasant sounds A, the humming sounds B and the pleasant sounds C.

The relationship between $N_{\text{ratio}}$ and the sharpness values according to the DIN 45692 standard is given in Figure 6 for all 35 fan sounds sorted according to the 5 groups of sounds which were identified with the factor analysis.

The group of unpleasant sounds A (filled squares in Figure 6) is spread over a broad range of sharpness values, largely overlapping with the sounds of the other groups in the direction of the ordinate. The group of pleasant sounds C (filled circles in Figure 6), although only consisting of four sounds, is visually better distinguished from the other groups of sounds. Despite a single sound from sound group B, values of $N_{\text{ratio}}$ larger than 1 in the direction of the abscissa are only found for the four sounds from sound group C.

To quantify the performance of the two new indexes, $N_{\text{ratio}}$ and $N_{\text{low}}$, in differentiating the three signal groups,



Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only

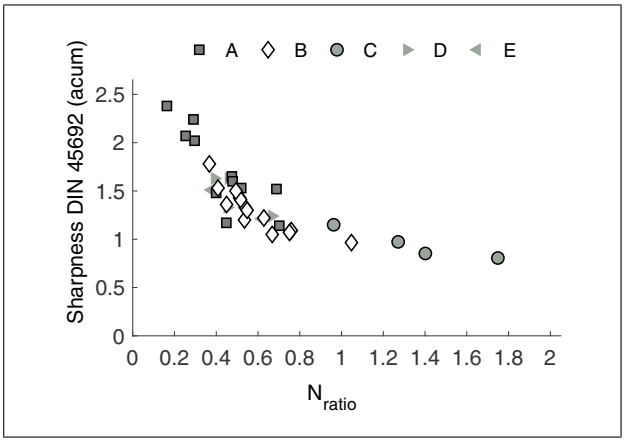



Figure 6. Scatter plot of the values of the proposed index $N_{\text{ratio}}$ and the sharpness according to the DIN 45692 standard for the 35 investigated fan signals. The five groups of sounds A to E (identified by the second PCA, Table III) are indicated by the symbols. The group of pleasant sounds (C, filled circles) are better separated from the rest of the sounds by the index $N_{\text{ratio}}$ than by the sharpness.

a k-means clustering algorithm was applied to standardized values of the $N_{\text{ratio}}$-$N_{\text{low}}$ scatter plot (using a z-transformation) to partition the data into three clusters. The assignments of the sounds to the clusters by the k-means algorithm were compared with the assignments of the sounds to the sound groups resulting from the second factor analysis (Section 3.2.3) for two different distance measures. For a distance measure based on the sum of the absolute differences, the assignments to the clusters by the k-means algorithm differs from the assignment to the sound groups for only 14% of the sounds. For a squared euclidean distance, the assignments to the clusters differs from the assignment to the sound groups for only 10% of the sounds. According to the Calinski-Harabasz index and the Davies–Bouldin index, a number of three clusters is optimal for our data set, provided a division of up to three possible clusters with a k-means algorithm. From these classification results it can be concluded that the two proposed indexes $N_{\text{ratio}}$ and $N_{\text{low}}$ effectively differentiate between the three main groups of sounds, A, B and C, which already include 80% of the sounds.

### 4.3. Relationships between the proposed indexes and the factor values

The relationships between the mean factor values of the first three perceptual dimensions, the sharpness according to the DIN standard [20] and the two proposed indexes, $N_{\text{ratio}}$ and $N_{\text{low}}$, are shown in Figure 7. A close relationship between the values of the pleasant dimension I and the sharpness, shown in Figure 7(a) with a correlation coefficient of $r = -0.71$ is observed. Sounds with small sharpness values are generally more pleasant than sounds with high sharpness values. This is well in line with previous studies where an increase in sharpness is often found to be linked to an increase in annoyance or a decrease in pleasantness judgments [13, 14, 15, 16, 17, 18, 19]. The sharpness is only weakly related to the factor values of the perceptual dimensions II (humming/bass, $r = -0.43$) and III (shrill, $r = 0.47$).

The proposed loudness ratio $N_{\text{ratio}}$, shown in Figure 7(b), has an even higher correlation coefficient with the factor values of the pleasant dimension I than the sharpness. The correlation coefficient is $r = 0.80$. Similar to the sharpness, the relationship between $N_{\text{ratio}}$ and the second II (humming/bass) and third dimension III (shrill) is rather weak.

The index $N_{\text{low}}$ is positively correlated to the humming/bass dimension II in Figure 7(f). The correlation coefficient is $r = 0.85$. In addition, $N_{\text{low}}$ is also negatively correlated to the shrill dimension III shown in Figure 7(i), with a correlation coefficient of $r = -0.67$. Surprisingly, a low amount of loudness in the very low frequencies seems to describe the shrillness of the fan sounds better than the exponentially increased weighting of the high frequencies in the calculation of the sharpness shown in Figure 7(g).

In addition to the differentiation between the three main groups of sounds (shown in Figure 5), the two rather simple indexes $N_{\text{ratio}}$ and $N_{\text{low}}$ derived from the analysis of the specific loudness patterns correlate well with the three main perceptual dimensions of the fan sounds.

To check whether the weighting functions of the indexes were optimally chosen, variations of the upper boundary in the weighting function $w_0$ of the index $N_{\text{low}}$ and of the center frequency of the weighting function $w_1$ from the index $N_{\text{ratio}}$ towards lower or higher frequencies were also tested. None of the variations yielded higher correlation coefficients with the factor values of the respective perceptual dimension. Thus, the choice of the parameters for the two indexes seems to be well suited for the characterization of fan sounds.

## 5. Discussion

In this study of 35 fan sounds, the factorial analysis of the results from the semantic differential disclosed six perceptual dimensions (I pleasant, II humming/bass, III shrill, IV monotone, V reverberant and VI noise-like) and five different groups of sounds (A unpleasant, B humming, C pleasant, D noise-like and E varied). Based on the analysis of the specific loudness for the five groups of sounds, two indexes ($N_{\text{ratio}}$ and $N_{\text{low}}$) could be derived which enable a characterization of the three major perceptual dimensions and an effective differentiation between the first three groups of sounds.

The six perceptual dimensions identified in the present study are in good agreement with those found by Feldmann *et al.* [6] even though, in the present study, the stimulus set was considerably broader and the semantic differential was developed based on a free verbalization by non-expert participants. The first dimension (quality) of Feldmann *et al.*, which reflects the evaluation of the sounds, is in good agreement with the first dimension I (pleasant) of the present study. Their second dimension (spectral content I) has high loadings of the adjective pairs *completely*



Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only

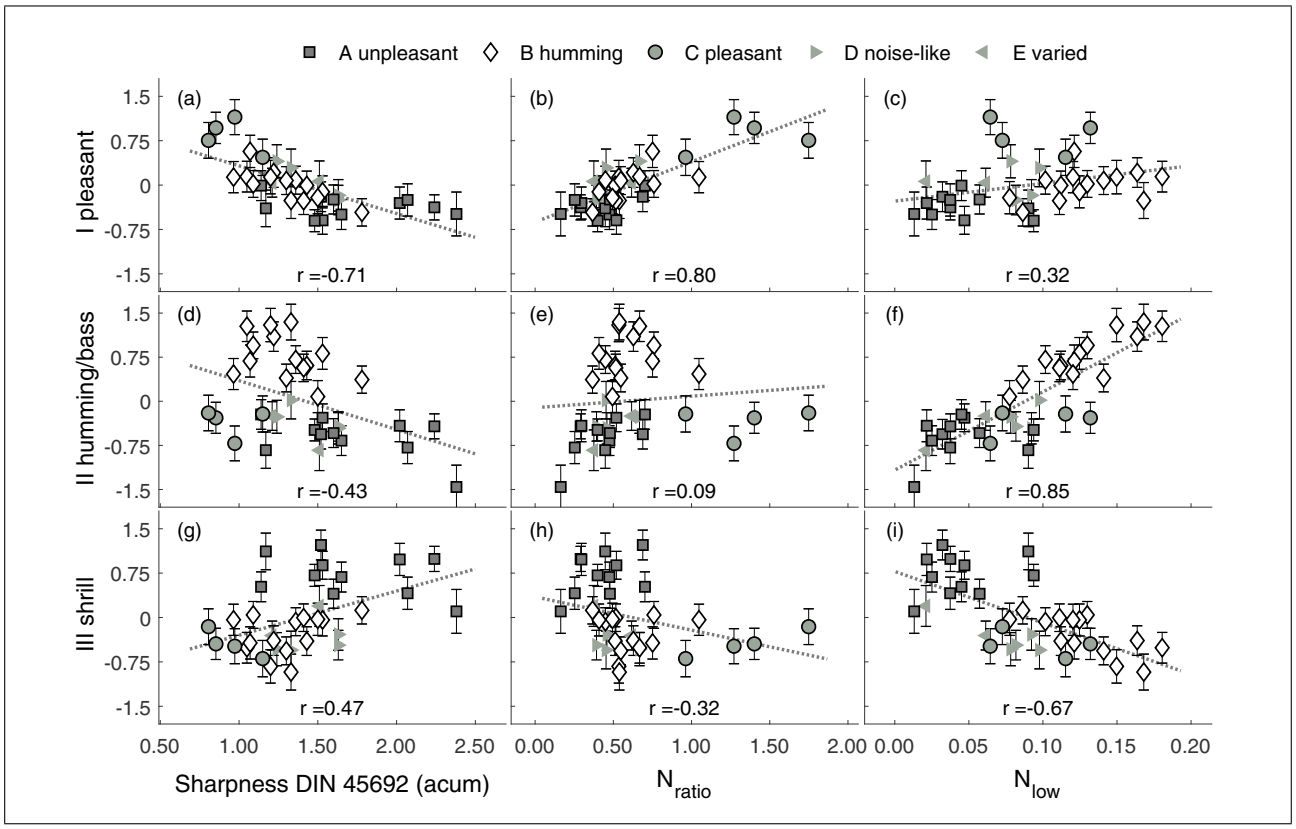



Figure 7. Mean factor values of the first three perceptual dimensions plotted over the sharpness (according to the DIN 45692) and the indexes $N_{ratio}$ and $N_{low}$. Errorbars show the 95% confidence interval and the five groups of sounds A to E (identified by the second PCA, Table III) are indicated by the symbols. Linear regressions are presented as dotted lines and correlation coefficients are given at the bottom of each plot.

*humming - not at all humming*, *dark - bright*, *completely roaring - not at all roaring* which closely corresponds to our second dimension II (humming/bass). Their third dimension (time structure) is similar to the fourth dimension IV (monotone), here. Their fifth dimension (power) is included into the second dimension II (humming/bass) by high loadings of the adjective scale *powerless - powerful* onto this factor. The last dimension from Feldmann *et al.* (spectral content II) is split into the two dimensions III (shrill) and VI (noise-like) of the present study. Thus, all of the perceptual dimension are mutually identifiable and the first two dimensions can be consistently identified even though the specific adjective scales were considerably different in both studies. This supports the general robustness of the identified perceptual dimensions over the investigated 35 sounds of the present study and the smaller subset of only eight sounds in the study of Feldmann *et al.* [6].

The identified perceptual dimensions are also in overall agreement with those found by Sung *et al.* [8]. Based on a factor analysis of ratings on 17 adjective scales, they identified four perceptual dimensions denoted "loudness", "tonal/sharpness", "irregular/fluctuation" and "not musical". Their first dimension (loudness) also shows high loadings of the adjectives *not acceptable* and *extremely annoying* which is similarly found for the first dimension I (pleasant) of the present study. The second factor from Sung *et al.* (tonal/sharpness) covers the aspect of tonality as well as the sharpness of the sounds. This indistinguishability between the two aspects is in overall agreement with the third dimension III (shrill) of the present study with high loadings of the adjective scales *not buzzing - buzzing*, *not squeaking - squeaking* and *jarring - dull*. Their third factor (irregular/fluctuation) is similarly found as the fourth dimension IV (monotone). Their weaker last factor (not musical), which is dominated by a single item does not show up in the present study because an item related to music was not a part of the semantic differential, here. The adjective scales used in the present study cover most of the words from the collection of Sung *et al.* for HVAC&R noises [7]. Especially the words that were mentioned most commonly by the participants of their study were also part of the adjective scales of the present study. Only those words which were classified under the term *impulsiveness* by Sung *et al.* were not part of the present adjective scales. However, the second dimension II (humming) of the present study was not separately identified in the study of Sung *et al.*. This finding and also the missing adjective pairs might be explained by the differences between the sets of sounds investigated by Sung *et al.* and in the present study.

The six perceptual dimensions identified in the present study also cover the three dimensions which were found by Minard *et al.* for HVAC sounds in cars [11]. The "pleasant" dimension from the study of Minard *et al.* directly



*Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only*

matches the first dimension I (pleasant) of the current study. Their "sharpness" dimension is similarly identified here as the third dimension III (shrill) and their "fluctuation" dimension is in overall agreement of the fourth dimension IV (monotone) of the present study. The semantic differential of Minard *et al.* consisted of a smaller set of 12 adjective scales which might explain the smaller number of identified dimensions in their study.

Similar like in the studies of Minard *et al.* [11] and also Sung *et al.* [8], the sensation of loudness is loading on the same dimension as the unpleasantness in the present study. In both of these two studies, loudness or level equalizations are not mentioned, whereas in the present study the sounds were equalized in terms of A- weighted levels. The differences in the mean loudness judgments between the groups of sounds (in Figure 2) indicate that the equalization in terms of the A-weighted level is apparently not sufficient to make the sounds equally loud.

In many studies, only one perceptual dimension linked to the spectral distribution of energy appears which is then often described by an index like the spectral centroid [9] or the sharpness [13, 14, 15, 16, 17, 18, 19]. In contrast to these findings, perceptual aspects related to very low frequency content (dimension II: humming/bass) and aspects related to high frequency content (dimension III: shrill) were found on two separate dimensions in the present study. This is also a major similarity of the present study and the study from Feldmann *et al.* which also identified two dimensions (spectral content I and spectral content II) related to the spectral content [6]. This distinction between low and high frequency content and the systematic differences in the patterns of the specific loudness were the reason to derive the two new indexes which specifically address the two different aspects of the sound character. The relation between low mid frequencies and higher frequencies, which is closely linked to the unpleasantness of the sounds, is characterized by $N_{\mathrm{ratio}}$. The aspect of humming/bass due to very low frequency components is described by the index $N_{\mathrm{low}}$. In this way, it became possible to effectively distinguish between the three major groups of sounds A (unpleasant), B (humming) and C (pleasant). To our surprise, the parameter targeted to describe the low frequency content ($N_{\mathrm{low}}$) yielded also a high negative correlation coefficient with the third dimension (shrill). Apparently, the absence of very low frequency content describes the aspect of shrillness overall better for the investigated sounds than high weightings for high frequency content like in the sharpness algorithm.

Parizet *et al.* successfully used a loudness balance which related the very low frequency content below 200 Hz (2 Bark) to a band from 2000–4000 Hz (13–18 Bark) for the preference ranking of high-speed train interior noise [23]. Based on a cluster analysis, they identified three groups of participants which used different criteria for their preference decision. The first and the third group of participants preferred higher values of the loudness balance while the second group had a preference for lower values. Their definition of the loudness balance encompasses the aspect of a spectral balance and a consideration of the very low frequency content up to 2 Bark which were also identified as being relevant for the fan sounds of the present study. Therefore, the loudness balance (according to [23]) was also tested as a potential index for the factor values of the first three dimensions from the present study. The correlation coefficients with the factor values of the first three perceptual dimensions are $r = 0.57$ (I unpleasant), $r = 0.69$ (II humming/bass) and $r = -0.61$ (III shrill), which are all lower than the correlation coefficients with the corresponding, specifically derived indexes $N_{\mathrm{ratio}}$ and $N_{\mathrm{low}}$.

However, the definitions of the frequency ranges which were identified from the analysis of the specific loudness patterns in the present study are in good agreement with the study of Alayrac *et al.* [24], characterizing industrial sounds, and the study of Ih *et al.* [19], evaluating sounds from air cleaners. The index $N_{\mathrm{low}}$ which was derived in the present study to characterize the perceptual aspect of humming/bass is also very similar to approaches for the characterization of the booming noise inside cars. Hatano and Hashimoto developed a so called booming index to describe the booming sensation resulting from coinciding firing orders of the engine and resonances of the cavity inside a car [21, 22]. The booming index includes exponentially higher weights for low frequency components below 280 Hz which were determined in listening test with bandpass filtered noise. The correlation coefficient between the booming index (according to [22]) and the factor values of the second dimension II (humming/bass) is $r = 0.66$. Hence, a description of the low frequency content which is simply based on the specific loudness up to 2 Bark seems to work better for the investigated fan noise signals than the exponential weighting of the very low frequencies included in the booming index. The overall agreement of relevant frequency ranges identified in the present study with such a broad range of literature references further suggests the eligibility of the proposed indexes, especially for a description of rather large differences in the sound character.

In the present study, a close link between the values of the pleasantness factor and the proposed index $N_{\mathrm{ratio}}$ was found. Sounds with higher values of $N_{\mathrm{ratio}}$ were overall more pleasant than sounds with low values of $N_{\mathrm{ratio}}$. This is in good agreement of the study of Jeon *et al.* [10] on the acoustic comfort of air-conditioning sounds. In their study, increases of the energy in the frequency range from 250–630 Hz for a fixed A-weighted overall level were linked to higher values on their "comfort" factor, for sounds with and also without prominent tonal components. Such an increase of the energy in the frequency range of 250–630 Hz would lead to higher values for the proposed index $N_{\mathrm{ratio}}$ which was found to be positively correlated with the pleasantness of the fan sounds in the present study.

In the study of Ih *et al.* on the sound quality of air cleaners, an increase of frequencies below 400 Hz by +6 dB combined with a reduction of the high or the mid and high frequencies was found to be beneficial [19]. Such a signal manipulation would lead to higher values for $N_{\mathrm{low}}$ and



Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only

to higher values for $N_{ratio}$, which was found to be linked to more pleasant sounds in the present study. Thus, the proposed new indexes might, in principal, also correctly describe the data of these two studies from the literature.

Fan sounds often contain audible tonal components leading to a sensation of tonality which was often found to be linked to the unpleasantness [9, 11] or annoyance of the sound [17, 34]. In the present study, however, the aspect of tonality did not appear explicitly in the development of the semantic differential although many of the investigated fan signals contained audible single or even multiple tones. In the collection of descriptive adjectives of experiment 1, a small number of adjectives related to the description of tonal content were mentioned by only some of the participants. Therefore, the adjective pairs *not whistling - whistling* (German: nicht pfeifend - pfeifend), *not squeaking - squeaking* (German: nicht fiepend - fiepend), *toneless - tonal* (German: tonlos - tonal), *not crooning - crooning* (German: nicht summend - summend) and *not fluting - fluting* (German: nicht flötend - flötend) were part of the initially composed 106 adjective pairs. Nevertheless, all but one of the scales were rejected based on the set selection criterion of a median rating of at least four scale units in the suitability ratings. The only remaining adjective pair describing tonal aspects, *not squeaking - squeaking*, is loading highly on the third perceptual dimension III (shrill) together with the adjective pairs *not buzzing - buzzing* and *jarring - dull* which describes the distribution of low and high frequency content. The adjective pair *jarring - dull* is also quite close to a description of sharpness in German language. It seems as if the amount of low frequency content (resulting in the second dimension II: humming/bass) and the overall high frequency content (reflected by the joint third dimension III: shrill) were more salient for the participants than a clear distinction between sounds with or without tones. Similarly, the aspect of tonality is also not very prominently present in the study of Feldmann *et al.* [6]. In their study the adjective scale *completely whistling - not whistling at all* was highly loading onto the same factor as the adjective scales *completely hissing - not hissing at all*, *completely noisy - not noisy at all* and *completely abrasive - not abrasive at all* and the factor was labeled rather neutrally spectral content II.

Even though the particular adjective scales were different to those in the study of Feldmann et al. and to those the present study, items related to tonality like e.g. *not tonal - very tonal* and items related to the distribution of low and high frequency content like *dull - sharp* similarly formed one joint factor in the study of Sung *et al.* [8]. Consequently, the role of tonality and high frequency spectral content for the evaluation of fan noise should be further investigated in future research. A variation of the tonal content by parametric signal manipulations might be helpful for a better distinction between the impact of overall spectral content and tonality on the assessment of the sounds and to characterize their effect more precisely [35].

## 6. Conclusion

For fan sounds, six perceptual dimensions were identified with a specifically tailored semantic differential. Five groups of sounds could be identified and characterized based on their pronounced semantic profiles.

In the analysis of the specific loudness for the groups of sounds, distinct patterns could be identified that led to the derivation of two new indexes, $N_{ratio}$ and $N_{low}$, which are based on loudness ratios between different frequency ranges. The proposed indexes seem to provide a sound foundation for a characterization of a broad variety of fan sounds because they enabled a clear differentiation between the three major groups of sounds covering unpleasant, humming and pleasant sounds. The results suggest that higher values for $N_{ratio}$ together with medium values for $N_{low}$ may result in more pleasant fan sounds.

The proposed indexes are of course limited to a rather course description of the overall spectral content which might nevertheless be more appropriate for the characterization of fan sounds than just using the sharpness as a single parameter, especially to precisely characterize the impact of very low frequency content.

The findings are in good agreement with several studies investigating the (un-)pleasantness of broadband sounds in different contexts which supports the robustness of the indexes and also their potential applicability in other fields.

An appropriate description of the temporal aspect of regularity and a more detailed characterization of the spectral fine structure including complex tonal signatures could be meaningful extensions of the work presented here which may be addressed in future work.

### Acknowledgements

The present study is part of a larger project dealing with the psychoacoustic characterization of fan noise, which was initiated by the "Forschungsvereinigung für Luft- und Trocknungstechnik FLT e.V." from Germany. The project is supported by the German federal ministry for economic affairs and energy (BMWi) on the basis of a decision by the German Bundestag. This is highly acknowledged by the authors. The authors would like to thank Takeo Hashimoto for providing code for the calculation of the booming index [22].

### References

[1] R. Sottek, K. Genuit: Sound quality evaluation of fan noise based on advanced hearing-related parameters. Noise Control Eng. J. **57** (2009) 384–390.

[2] R. Guski: Psychological methods for evaluating sound quality and assessing acoustic information. Acta Acust. United Ac. **83** (1997) 765–774.

[3] P. Susini, G. Lemaitre, S. McAdams: Psychological measurement for sound description and evaluation. In: Measurement with Persons: Theory, Methods, Implementation Areas. Psychology Press, New York, 2011, 227–253.

[4] N. Chouard, T. Hempel: A semantic differential design especially developed for the evaluation of interior car sounds. In: Collected Papers from the Joint Meeting “Berlin 99”



Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only

137th regular meeting of the Acoustical Society of America 2nd convention of the EAA: Forum Acusticum - integrating the 25th German Acoustics DAGA Conference. DEGA e.V., Berlin, 1999.

[5] M. E. Altinsoy, U. Jekosch: The semantic space of vehicle sounds: Developing a semantic differential with regard to customer perception. J. Audio Eng. Soc. **60** (2012) 13–20.

[6] C. Feldmann, T. Carolus, M. Schneider: A semantic differential for evaluating the sound quality of fan systems. Proc. ASME Turbo Expo 2017, Charlotte, USA, 1–8, GT2017–63172, 2017.

[7] W. Sung, P. Davies, J. S. Bolton: Descriptors of sound from HVAC&R equipment. Proc. Noise-Con 2017, Grand Rapids, United States, 2017, 1–9.

[8] W. Sung, P. Davies, J. S. Bolton: Results of a semantic differential test to evaluate HVAC&R equipment noise. Proc. Inter-Noise 2017, Hong Kong, 2017, 5377–5385.

[9] P. Susini, S. McAdams, S. Winsberg, I. Perry, S. Vieillard, X. Rodet: Characterizing the sound quality of air-conditioning noise. Appl. Acoust. **65** (2004) 763–790.

[10] J. Y. Jeon, J. You, C. I. Jeong, S. Y. Kim, M. J. Jho: Varying the spectral envelope of air-conditioning sounds to enhance indoor acoustic comfort. Build. Env. **46** (2011) 739–746.

[11] A. Minard, C. Lambourg, P. Boussard: Perceptual evaluation of the sound quality of car HVAC systems. Proc. Inter-Noise 2016, Hamburg, Germany, DEGA e.V., Berlin, 2016, 4467–4474.

[12] ISO 1996-2-2007: Acoustics - Description, measurement and assessment of environmental noise – Part 2: Determination of environmental noise levels. International Organisation for Standardization, 2007, 1–40.

[13] G. von Bismarck: Timbre of steady sounds: A factorial investigation of its verbal attributes. Acustica **30** (1974) 146–159.

[14] W. Aures: Der sensorische Wohlklang als Funktion psychoakustischer Empfindungsgrößen (The sensory euphony as a function of auditory sensations). Acustica **58** (1985) 282–290.

[15] S. Hohls, T. Biermeier, R. Blaschke, S. Becker: Psychoacoustic analysis of HVAC noise with equal loudness. Proc. Inter-Noise 2014, Melbourne, Australia. Australian Acoustical Society, 2014, 1–7.

[16] V. Wagner, H. Enigk, T. Beitz, K. W. Kallus: Subjective and objective evaluation of the air conditioning sound. J. Ergonomics **4** (2014) 1–5.

[17] M. S. Khan, C. Högström: Determination of sound quality of HVAC systems on trains using multivariate analysis. Noise Control Eng. J. **49** (2001) 276–283.

[18] M. E. Altinsoy: Towards an european sound label for household appliances: Psychoacoustical aspects and challenges. Proc. PQS 2013 - 4th International Workshop on Perceptual Quality of Systems, Vienna, Austria, 2013, 1–6.

[19] J. G. Ih, S. W. Jang, C. H. Jeong, Y. Y. Jeung, K. S. Jun: A study on the sound quality evaluation model of the air cleaner. Proc. IMECE 2007, Seattle, USA, 2007, 523–526.

[20] DIN 45692:2009: Measurement technique for the simulation of the auditory sensation of sharpness. Beuth, Berlin, Germany, German industry standard, 2009, 1–14.

[21] S. Hatano, T. Hashimoto: Modification of booming level for higher correlation with booming sensation. JSAE Review **20** (1999) 123–125.

[22] S. Hatano, T. Hashimoto: Booming index as a measure for evaluation booming sensation. Proc. Inter-Noise 2000, Nice, France, SFA, 2000, 1–5.

[23] E. Parizet, N. Hamzaoui, J. Jacquemoud: Noise assessment in a high-speed train. Appl. Acoust. **63** (2002) 1109–1124.

[24] M. Alayrac, C. Marquis-Favre, S. Viollon, J. Morel, G. Le Nost: Annoyance from industrial noise: Indicators for a wide variety of industrial sources. J. Acoust. Soc. Am. **128** (2010) 1128–1139.

[25] M. Schneider, C. Feldmann: Psychoacoustic evaluation of fan noise. Proc. Fan 2015, Lyon, France, 2015, 1–12.

[26] P. Susini, O. Houix, G. Saint Pierre: The effect of loudness on the perceptual representation of sounds with similar timbre. Acta Acust. united Ac. **101** (2015) 1174–1184.

[27] C. Feldmann, M. Schneider, T. Carolus: Psychoakustische Beurteilung von Ventilatoren mit der Methode des semantischen Differentials (Psychoacoustic evaluation of fans with the method of the semantic differential). Fortschritte der Akustik - DAGA 2016, Aachen, Deutschland, DEGA e.V., Berlin, 2016, 904–906.

[28] S. Namba: On the psychological measurement of loudness, noisiness and annoyance: A review. J. Acoust. Soc. J. (E) **8** (1987) 211–222.

[29] A. Field: *Discovering Statistics using SPSS*. SAGE Publications Ltd., London, 3. edition, 2009.

[30] J. P. Stevens: Applied multivariate statistics for the social sciences. Taylor & Francis, New York, 5. edition, 2009.

[31] DIN 45631:1991: Procedure for calculationg loudness level and loudness. Beuth, Berlin, Germany, German industry standard, 1991, 1–27.

[32] ISO 532-1977: Acoustics - Method for calculating loudness level. International Organisation for Standardization, 1977, 1–18.

[33] J. Scheuren: ISO 532 - Living and working with alternative loudness standards. Proc. Inter-Noise 2014, Melbourne, Australia, Austrian Acoustical Society, 2014, 1–6.

[34] J. Lee, Jennifer M. Francis, Lily M. Wang: How tonality and loudness of noise relate to annoyance and task performance. Noise Control Eng. J. **65** (2017) 71–82.

[35] W. Sung, P. Davies, J. S. Bolton: A methodology to modify steady state heating, ventilating, air conditioning and refrigeration equipment noise. Proc. Noise-Con 2016, Providence, United States, 2016, 252: 299–306.



*Document downloaded by @DAEL, 2026-11-20 03:57:22 - personal use only*