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The Semantic Space of Vehicle Sounds: Developing a Semantic Differential with Regard to Customer Perception

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Evaluating the sound quality of a vehicle is a complex process. Physical and psychoacoustical measures cannot sufficiently describe this process with only superficial cues. Customer quality evaluation is based on their perceptions, interpretations and expectations. This study generated a semantic space for vehicle sound. In other words, we elicited numerous attributes related to the perception and quality of vehicle sound. We sought to determine customers' common language that appropriately describes vehicle sound quality. This study developed and applied a novel systematic approach, which includes a free verbalization interview, a test of participants' understanding of acoustic attributes, and participant evaluation of the ability of these attributes to describe perceptible vehicle sound properties. In this manner, we created a complete semantic database to describe vehicle sounds and testing the relevance and redundancy of these attributes. At the end of the investigation, we developed two sets of 28 attributes for interior and exterior driving conditions.

0 INTRODUCTION

People judge a product to be high quality when their expectations are met or exceeded [1, 2]. Quality features of industrial products include functionality, safety and usefulness, but there are also aesthetic and emotional aspects [3]. These features must be created in such a way that they comply with the general product design. In other words, the goal of design is to create an object that stimulates and satisfies customer interests. Customer interests are satisfied when the designed product leads to a harmonic perceptual entity [1, 4].

Vehicle sound quality is a complex phenomenon. Customers' perceptions, interpretations, and expectations play an important role in the evaluation of vehicle sound quality. Therefore, physical and psychoacoustical measures cannot sufficiently describe this process. It is necessary to determine customers' common language that appropriately describes vehicle sound quality. However, the majority of vehicle sound quality research investigates semantic spaces using trained listeners or vehicle acousticians. They decide which attributes should be used in semantic differentials [5, 6, and 7]. The advantages of using trained or expert listeners include their ability to provide usable data with relatively few iterations and their ability to identify small differences among stimuli [8]. However, experts' knowledge, tastes, interpretations, and expectations may differ strongly from those of the targeted customers. This point is particularly important given the wide variety of vehicle makes and models. This study investigates the semantic space of interior and exterior vehicle sounds using only customers without technical backgrounds or specific acoustic knowledge. Furthermore, the purpose of this paper is to describe and explore a novel systematic approach for the development of a semantic differential for vehicle sound. This systematic approach may also be applied to generate the semantic space of other product sounds.

1 BACKGROUND

1.1 Elicitation Techniques

Various elicitation techniques may be used to elicit verbal descriptors [9, 10]. All techniques, however, have weaknesses as well as strengths. Free verbalization methodology is one of the verbal elicitation techniques [11]. In this approach, people speak while performing a task. Researchers analyze and interpret participants' statements to examine the nature of the task. The main weaknesses of this methodology are that individual verbal protocols are not directly suitable for generating a common semantic differential and the interpretation of the individual protocols by an expert is critical regarding possible knowledge, taste and expectation differences between him and target customers.

In recent years, the repertory grid technique (RGT) and perceptual structure analyses (PSA) have successfully elicited auditory attributes of multichannel sound [8, 12]. RGT consists of two parts: the elicitation of verbal descriptions and the rating of these descriptions. First, participants are presented with triads of stimuli and are asked to indicate which of the three sounds differs from the other two the most. Participants then describe the ways in which two of the stimuli are alike as well as different from the third. Second, participants rate each of the stimuli based on the constructs elicited in the first part. PSA also presents participants stimuli triads. Participants identify acoustic features but do not name them. This approach requires that the participants have a clear idea of these sounds before proceeding [12]. Therefore, PSA requires an extensive training session. Both methodologies have difficulties with the large number of stimuli, because of the long duration.

1.2 Categorization of Verbal Descriptors

Comprehensive studies have attempted to create a lexicon for everyday sound events [13, 14]. These investigations began by collecting 450 words from the psychoacoustic, sound quality and product sound quality literature, with supplemental findings from dictionaries and thesauruses. Researchers divided these terms into the following groups: direct sound descriptions, words related to non-auditory perceptions, references to acoustic events, changes in perceptions, affective responses to sounds, connotative associations and onomatopoeia. In the next step, experts rated these words according to 17 primary dimensions (e.g., loudness, duration, tempo and so on). Researchers used the standard deviations of these ratings to understand how different people interpret the similarities of these terms.

2 METHOD

The aim of this study was to elicit numerous attributes related to the perception and quality of vehicle sound. The development of an attribute scale (i.e., a semantic differential) will be based on this semantic space. Therefore, we sought to determine a common language among customers that appropriately describes vehicle sound quality. This study applied the free verbalization technique due to the large number of stimuli. In this technique, participants do not compare stimuli directly. Therefore, the duration of this method is usually shorter than that of other techniques.

We obtained a common set of attributes comprising successive steps of an investigation (Fig. 1). In the first step (the free verbalization interview), participants listened to vehicle sounds and described their auditory impressions. This step resulted in a list of descriptive attributes. In the next step, we checked whether all participants understood these attributes and asked them to evaluate the suitability of these attributes to describe perceptible vehicle sound properties. We excluded terms when they were not associated with a meaning for any participant. In the same step, a quasi-continuous scale evaluated the suitability of these attributes. Suitability judgments provided a basis for excluding the terms that do not sufficiently describe vehicle sounds. Next, we conducted a semantic differential test using the remaining attributes. A cluster analysis of the semantic differential data provided important clues regarding the similarity of the terms. Thus, checking attribute redundancies was possible.

Independently of the semantic differential investigation, the vehicle sounds were evaluated pair-wise to determine their similarity. The dissimilarity distance between sounds is the result of the differences perceived between their descriptive terms. Therefore we claim that the correlation between the sound dissimilarity ratings and the sums of their perceived differences is an indicator of the completeness of the semantic database. Consequently, we compared the results obtained in the semantic differential and similarity investigations to understand whether the remaining adjectives successfully described the interior and exterior vehicle sound (Fig. 1, completeness check). Finally, we evaluated the repeatability of the participants' judgments.

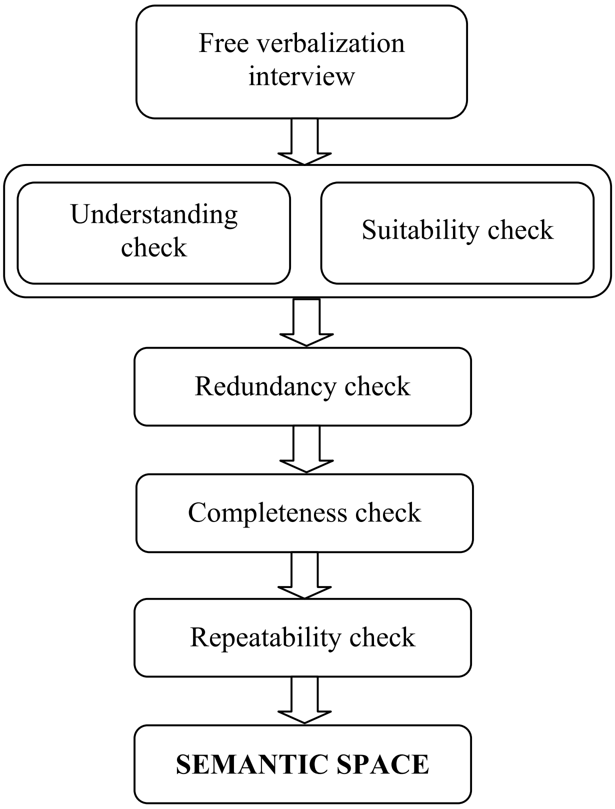

Fig. 1. Steps of the Investigation.

The investigation was run in individual sessions. Because context is an important aspect of this study, we conducted a training session for each subject. In the 15-minute training phase, we used visual materials (e.g., video recordings of the driving condition and pictures of the route) to describe the driving conditions to participants.

2.1 Stimuli

We selected representative vehicle types and real-life driving situations for this investigation and presented the binaurally recorded sounds of 24 cars in eight driving conditions from different brands with different motorization to the participants. The driving conditions depended upon the listener's location:

- Interior
    - Engine start
    - Engine idle
    - Acceleration
    - Passing maneuver
- Exterior
    - Engine start
    - Engine idle
    - Slow passing maneuver
    - Fast passing maneuver

2.2 Subjects

The subjects were average customers who have no technical background or specific acoustic knowledge. Seventeen people (10 males and 7 females) participated in the first part of the study (the free verbalization interview). Their ages ranged between 22 and 53 years. Forty-one people (29 males and 12 females) participated in the additional portions of the study. Their ages ranged between 22 and 55 years. All subjects were native German speakers and had normal hearing ability. They were paid on an hourly basis.

3 DEVELOPING A SEMANTIC DIFFERENTIAL

3.1 Free Verbalization Interview

In this part of the study, participants describe all their auditory impressions during and after listening to the vehicle. This procedure elicited 682 different descriptive terms. We categorized these terms into four categories:

- Signal-related terms without emotional content (e.g., loud, dull and sputtering; 47 %)
- Physical property terms (e.g., small, new, luxurious and light; 13 %)
- Emotional terms (e.g., threatening, annoying and aggressive; 32 %)
- Vehicle type-related terms (e.g., minivan, turquoise, taxi, luxurious and sporty; 8 %)

We split these main categories into 16 groups (Table I). Some of the terms could be sorted into more than one category or one group.

Some participants also named vehicle makes (n = 70). Some of the terms that participants used were not clear. Therefore, we interviewed participants after the free verbalization phase; specifically, we asked if they could define the terms that were unclear. For example, one of the participants used the term "taxi". In the interview, we noticed that this participant experienced diesel vehicles only as a taxi passenger. Therefore, she associated the noise typical of diesel vehicles with taxis. Interestingly, some participants associated vehicle sounds with colors (e.g., black, turquoise and so on). The interview revealed that most participants unconsciously associate color with the frequency content of the vehicle sound. Some participants associated black with limousines. Color hearing is one of the well known phenomena of synesthesia and was also reported by previous studies [17, 18, and 19]. However, both synesthetes and non-synesthetes can match colors with sounds in a non-arbitrary way [20]. The participants who associated color with sound in this study did not claim to have synesthetic experiences. The level of audio-visual coupling, such as cross-sensory analogy, iconic coupling or symbolic connections, varied in different associations.

We observed that participants used different emotional terms for the same sound. For example, the same sound elicited the terms "exciting" and "bothersome". Other sounds evoked both "sporty" and "not comfortable".

Table I. Descriptive term categories

Gr. Nr.	Group name	Exemplar terms
1	Timbre	Dull, low-frequency
2	Power	High-powered, strong, strenuous
3	Intensity	Loud, moderate, smooth
4	Regularity	Constant, jerky, steady
5	Pleasantness	Bothersome, pleasant, coherent
6	Dimensions	Small, spacious
7	Onomatopoeia, nature	Humming, whining, booming
8	Distinctive features	Unremarkable, characteristic, extreme
9	Durability	Solid, qualitative, broken
10	Onomatopoeia	Hissing, rattling, squealing
11	Age	New, second hand, age-old
12	Sonority	Insulated, clear, solid
13	Image	Suitable for daily use, sporty, functional
14	Price	Cheap, valuable, affordable
15	General product features	Good, cost-saving
16	Technical associations	Turbine, turbo, diesel

3.2 Understandability and Suitability Checks

This study sought to acquire a common set of attributes across all panel members, rather than individualized attributes. Thus, we conducted two additional and consecutive tests to evaluate these terms based on their understandability and their suitability to describe acoustic vehicle properties. Panel members (n = 41) sorted the terms into groups of explicit meaning or driving-condition irrelevance. At the end of this categorization, we excluded the 63 irrelevant terms. A quasi-continuous Rohrmann scale was used to evaluate suitability ranging from "not suitable" to "extremely suitable" (the scale is described in more detail in Section 3.3). Participants used a GUI implemented in Visual Basic. We randomized the order of the terms across participants. Some terms were presented twice to check participant response reliability.

Fig. 2 outlines the results of the suitability investigation: 619 terms were almost equally distributed across the suitability scale. Based on these suitability judgments, we excluded all terms rated less than 75% of the maximum suitability value (dashed line in Fig. 2). This threshold value is assumed to be a good compromise for the exclusion of terms.

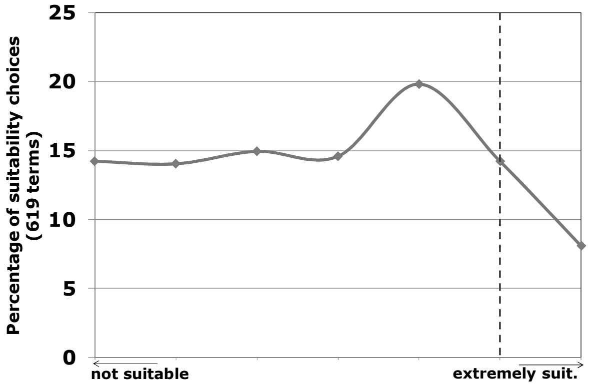

Fig. 2. The distribution of suitability ratings across 619 terms.

We determined the antonyms of 144 highly suitable terms. Most of these antonyms were already included in the 144-term list. Additionally, participants identified each term's antonym. Participants then evaluated pairs of antonyms based on their suitability as opposite verbal descriptions using a Rohrmann scale (from "not suitable" to "extremely suitable"). Approximately 46 % of the terms had clear antonyms. Onomatopoeic terms do not have antonyms. Thus, not all adjectives had an opposite.

3.3 Redundancy, Completeness and Repeatability Check

To obtain a common set of attributes, we tested additional criteria:

- Attribute redundancy
- Completeness of the semantic database
- Repeatability of the participants' judgments

To test the completeness of the vehicle sound database, we conducted similarity and semantic differential investigations. In the similarity investigation, we presented listeners with sound pairs. Listeners rated pair similarity using a quasi-continuous scale. The advantage of a similarity investigation is that the participants do not use linguistic labels. Therefore, this investigation is not related to linguistic capabilities of participants. The dissimilarity between sounds is the result of the differences perceived between their descriptive terms (Figure 5). This relationship can be described as follows:

$$\delta_{i,j} = a*(t_{1,i} - t_{1,j}) + b*(t_{2,i} - t_{2,j}) + ... + z*(t_{m,i} - t_{m,j}) \quad (1)$$

$\delta_{i,j}$ where is the dissimilarity between sound i and sound j, $t_{m,i}$ is the rating for the descriptive term m of sound i and a/b/…/z are the weights of the descriptive terms. The correlation between the dissimilarity rating and the sums of their perceived differences is an important criterion that ensures the completeness of the semantic database.

Next, we created a semantic differential using the descriptive terms determined previously. The sound database consisted of the interior and exterior sounds of 36 cars. Participants assessed the intensity of their associations (such as pleasantness, annoyance, etc.) on a continuous 100-point unnumbered graphical scale (Fig. 3 and 4). This scale consisted of a horizontal slider, which was marked with verbal anchors describing different intensities (not at all, slightly, moderately, very, and extremely). The verbal anchors were obtained from a study concerned with developing verbal labels for scale intervals that had shown that these particular labels were semantically equidistant from each other [21, 22]. Subjects were instructed to move the slider bar to the appropriate location on the scale, where their perceived intensity of sensation lay, using a mouse. The slider was 100 mm long and the score in this scale was equal to the distance (mm) of the bar from the left end. Fig. 3 shows the scale used for the terms that did not have an antonym, and Fig. 4 shows the scale used for the terms that did. These kinds of semantically labeled continuous scales were developed and popularly used in the study of taste and smell [23, 24] and later also in the study of hearing [25, 26].

To test attribute redundancy, we conducted a cluster analysis on the semantic differential data (i.e., the squared Euclidean distance) to determine term similarity. An agglomerative hierarchical algorithm (average linkage) was used. We excluded terms that had similar meanings from the database (altogether 73 terms pertaining to exterior noise and 77 terms pertaining to interior noise, e.g., hammering, buzzing and screaming). We retained only the terms that obtained maximum suitability ratings.

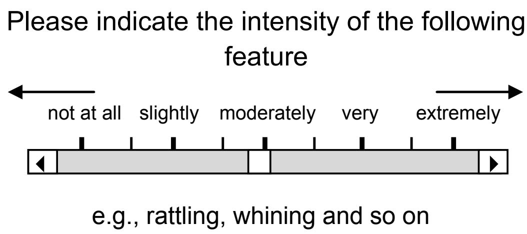

Fig. 3. The Rohrmann scale for the terms without an antonym.

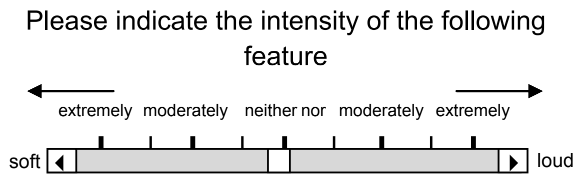

Fig. 4. The Rohrmann scale for the terms with an antonym.

The repeatability of participants' judgments showed robust meaning associations. To test this repeatability, we randomly selected ten attributes from the database to ask participants about twice during the semantic differential investigation. To avoid short-term memory effects, we repeated these terms in two separate sessions. The results of this repetition showed that participants agreed with their previous judgments. The maximum deviation of mean values was not higher than 8 %.

Next, we compared the results of the similarity and semantic differential investigation to check the completeness of the database (see Fig. 5). We determined that the correlation coefficient for the relationship between the sums of the attribute rating differences (weights = 1) and the similarity ratings was r = 0.91 (Fig. 6). Increasing this correlation coefficient by optimizing the regression weights is possible. The overall results showed that the remaining adjectives successfully described the interior and exterior vehicle sounds (Fig. 6).

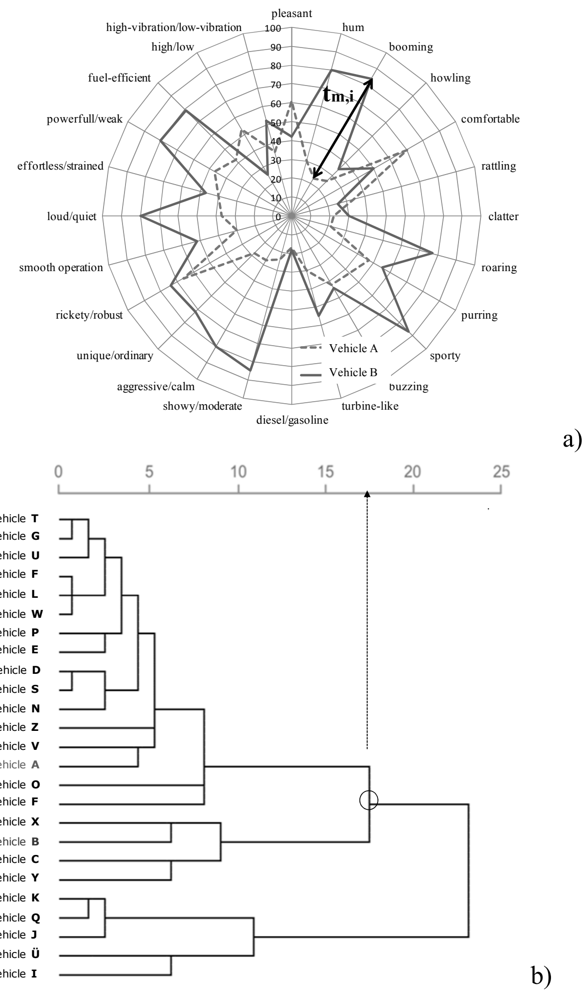

Fig. 5. A completeness check using the results of two vehicles. a) The results of the semantic differential; b) the similarity cluster analyses.

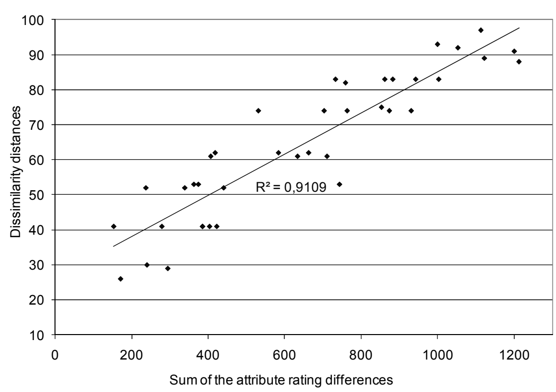

Fig. 6. The similarity ratings regression line (0 = similar; 100 = extremely dissimilar) and the sums of the attribute rating differences.

Table II. The set of exterior vehicle noise attributes.

Exterior noise	
Terms that have antonyms	
Low (tief)	High (hoch)
Weak (schwach)	Powerful (stark)
Quiet (leise)	Loud (laut)
Low-vibration (vibrationsarm)	High-vibration (vibrierend)
Calm (entspannt)	Aggressive (aggressiv)
Ordinary (gewöhnlich)	Unique (besonders)
Robust (robust)	Rickety (klapprig)
Moderate (dezent)	Showy (aufgemotzt)
High fuel consumption (verbraucht viel sprit)	Fuel-efficient (sparsam)
Gasoline (benziner)	Diesel (diesel)
Strained (angestrengt)	Effortless (mühelos)
Over-revved (überdreht)	Smooth (laufruhig)
Slow (langsam)	Fast (schnell)
Unimpressive (mickrig)	Impressive (mächtig)
Unpleasant (unangenehm)	Pleasant (angenehm)
Terms that do not have clear antonyms	
Hum (brummen)	
Booming (dröhnen)	
Howling (heulen)	
Comfortable (komfortabel)	
Rattling (rasseln)	
Clatter (rattern)	
Roaring (röhren)	
Purring (schnurren)	
Sporty (sportlich)	
Buzzing (summen)	
Turbine-like (turbinenartig)	
Annoying (lästig)	
Penetrating (penetrant)	

Based on the investigations mentioned above, we developed 8 sets of attributes for the 8 driving conditions. Each set contained 24 to 36 attributes. These sets are summarized in groups of interior and exterior noises (Tables 2 and 3) because of their comparability. The attributes were translated by two bilingual language specialists (American English – German) and discussed with the authors.

Table III. The set of interior vehicle noise attributes.

Interior noise	
Terms that have antonyms	
Low (tief)	High (hoch)
Quiet (leise)	Loud (laut)
Low-vibration (vibrationsarm)	High-vibration(vibrierend)
Calm (entspannt)	Aggressive (aggressiv)
Ordinary (gewöhnlich)	Unique (besonders)
Moderate (dezent)	Showy (aufgemotzt)
Robust (robust)	Rickety (klapprig)
High consumption (verbraucht viel sprit)	Fuel-efficient (sparsam)
Gasoline (benziner)	Diesel (diesel)
Weak (schwach)	Powerful (stark)
Regular (kontinuierlich)	Irregular (unregelmäßig)
Muffled (gedämpft)	Reverberant (hallend)
Unpleasant (unangenehm)	Pleasant (angenehm)
Terms that do not have clear antonyms	
Hum (brummen)	
Booming (dröhnen)	
Howling (heulen)	
Comfortable (komfortabel)	
Rattling (rasseln)	
Clatter (rattern)	
Roaring (röhren)	
Purring (schnurren)	
Sporty (sportlich)	
Buzzing (summen)	
Turbine-like (turbinenartig)	

4 DISCUSSION AND CONCLUSIONS

Our results show that the adjectives provided for interior and exterior noises have strong similarities. In particular, signal-related terms are the same across sets. Some attributes in the exterior noise set had emotional components, such as strained and troublesome. Some vehicle-related terms, such as powerful and fast, appeared only in the exterior noise set, while terms that are related to the acoustic condition of the vehicle's interior (e.g., reverberant) appeared only in the interior noise set, as expected.

The descriptive term categories found in this study are similar to the results of previous studies [9, 10, and 14]. In particular, signal-related terms and emotional terms comprise a majority of the adjectives.

Some of the terms elicited in this study are similar to terms elicited in previous studies (e.g., high, loud, irregular, booming, comfortable, sporty, strong, etc. [7, 9, 14, and 15]). However, previous research has not mentioned other terms (e.g., vibrating, aggressive, moderate, unique, showy and effortless). Participants without technical backgrounds or specific acoustic knowledge did not use or recognize some classic signal analysis parameters such as modulation. Rather, they used the term "vibrating" to describe sound modulation. Most participants felt that they could differentiate the sound of a diesel vehicle from that of a gasoline vehicle; however, they were unaware of the term "diesel knocking". Interestingly, they used some typical vehicle acoustician terms such as "booming", "clatter" and "roaring" to describe vehicle sounds.

In this study, a novel systematic approach was developed and successfully applied to generate a semantic differential for vehicle sounds. We belive that this approach can also be used in new investigations aimed at uncovering the semantic space of various product sounds.

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