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## Identification of quality attributes of automotive idle sounds and whole-body vibrations

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**Abstract:** The aims of this study are the generation and comparison of the semantic spaces of vehicle idling sounds and vibrations and the determination of their quality dimensions. In this study, two different sets of quality attributes were developed for idling sounds (34 attributes) and whole-body vibrations (22 attributes). In contrast to prior investigations, the results demonstrated that the sound level alone is an insufficient attribute for describing the complexity of idle sounds and vibration perceptions. The qualities of both idle sounds and idle vibrations have multidimensional, complex characters. The results show that intensity-dependent attributes, signal-based attributes in terms of spectrum and temporal properties, and comfort- and emotion-based attributes are all required to characterise the idling noise, vibration, and harshness (NVH) performance of vehicles. Therefore, an index was proposed based on psychoacoustic metrics such as loudness, sharpness, roughness, fluctuation strength, and relative approach. The results also show that emotional aspects play an important role for the assessment of sound and vibrations.

**Keywords:** sound quality; vibro-acoustic comfort; whole-body vibration; engine idling; vehicle interior noise; free verbalisation; RGT; semantic space; sound and vibration perception.

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**Biographical notes:** M. Ercan Altinsoy studied mechanical engineering at the Technical University of Istanbul and became a Research and Teaching Assistant at the Chair of Mechanical Vibrations and Acoustics. He received his PhD in Electrical Engineering from Ruhr University Bochum. After his PhD, he worked at HEAD acoustics as a NVH Consulting Engineer. In 2006, he started lecturing at the Dresden University of Technology, Chair of Communication Acoustics. He is leading the 'Audiotactile Interaction' group at the same university. His research interests include vehicle acoustics, vibroacoustics, product sound and vibration design, auditory and haptic interfaces for virtual environments, tactile psychophysics and psychoacoustics.

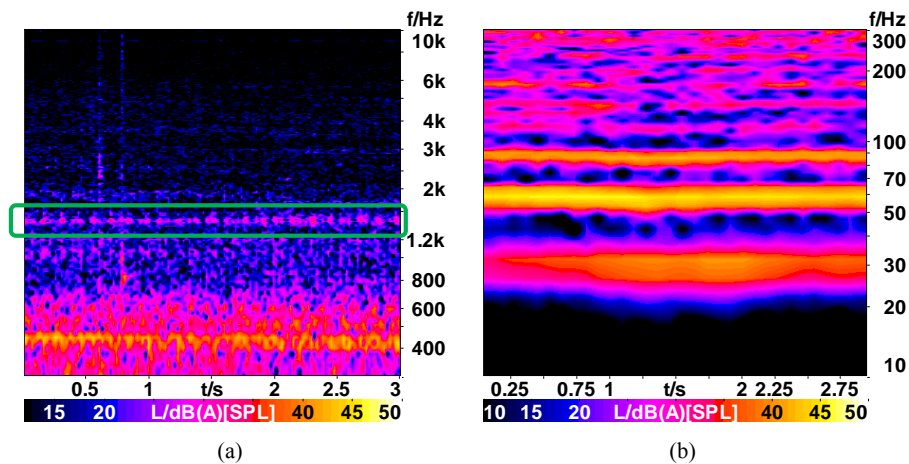
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### 1 Introduction

An important consideration for the noise, vibration, and harshness (NVH) engineer is that sound is usually produced by vibrations. Therefore, there is a strong relationship between

the physical properties of a sound and the physical properties of the corresponding vibration. The combustion engine and its ancillary units are the dominant sound sources in an automobile at idle. Thus, the idle sound is a characteristic of driving conditions that makes it possible to distinguish the type of combustion engine (diesel/gasoline) in use. Vehicles that are equipped with diesel engines generate a typical sound referred to as *diesel impulsiveness* or *diesel knocking* by NVH experts (Bodden and Heinrichs, 2007). The diesel sound has an impulsive signal component with a periodicity defined by cylinder firing (Figure 1). Another sound characteristic that is typical for the idle driving condition is the rattle (Feng and Hobelsberger, 1999), which is mainly caused by the transmission system. Sometimes, the combination of the transmission system and the engine causes a rattling sound. In addition to impulsiveness and rattle, booming is a typical sound phenomenon in idling conditions. The booming noise occurs when the frequency of excitation by the engine resonates with or is very close to an acoustic cavity mode of the vehicle interior (Matsuyama and Maruyama, 1998).

**Figure 1** The short-time Fourier transform (STFT)-based interior noise spectrograms of a diesel vehicle recorded during idling (see online version for colours)



Notes: Two different FFT lengths and frequency ranges were selected to better reveal the two different noise phenomena. (a) Diesel impulsiveness at 1.5 kHz (FFT length, 2,048; frequency range, 300 Hz – 10 kHz) and b) strongly noticeable engine orders at low frequencies, which cause booming (FFT length, 8,192; frequency range, 10 Hz – 300 Hz).

The seat and steering wheel vibrations experienced during idling are almost as interesting as the interior sounds (Ajovalasit and Giacomini, 2007; Altinsoy and Merchel, 2008; Parizet et al., 2007). The main sources of the vibrations in a car running at idle are the engine and the drive train because tyre and aerodynamic forces, which are important during other driving conditions, are not present in the idle state (Ajovalasit and Giacomini, 2007). Measurements at idle, particularly for diesel cars but also for gasoline cars, show the existence of high whole-body vibration levels at the main engine orders, which are above human perceptual threshold values (Altinsoy and Merchel, 2008). These types of vibrations are mostly coupled with a booming noise. Car burst shaking is another important vibration phenomenon that occurs during idling (Tüma et al., 2002). Irregular

combustion processes in cylinders cause random vibration impulses. Therefore, this vibration is characterised by dominant spectral components at 0.5 or 1.5 engine orders, accompanied by broadband excitation. The non-stationary impulsive character of car burst shaking is typically associated with quality problems. These technical terms *diesel impulsiveness*, *rattle*, *booming* and *car burst shaking* are used by NVH experts to describe the character of the sounds or vibrations.

Recently, an investigation was conducted to describe the quality of vehicle idling sounds using only signal-based parameters (Lee, 2006). Principal component analysis (PCA) and correspondence analysis (CA) were applied to analyse the entire frequency spectrum of sound pressure levels (SPLs) to characterise the differences in engine idle noises. The authors found that the overall SPL, the overall dB(A) over the entire frequency band and the SPL at lower frequencies between 25 Hz and 50 Hz are important parameters for characterising idle noises.

Customer demands are satisfied when a product design leads to a harmonic perceptual entity (Altinsoy and Jekosch, 2012). This satisfaction is the case when the perceived form of the product and the function it conveys are coherent. Apart from the form-function relation, coherence is also related to various information channels, i.e., sensory inputs. A driver receives information from several sensory channels when operating a car. Consequently, cross-modal information has a substantial influence on product quality evaluations. The quality evaluation of vehicle sounds and vibrations is a complex process. Physical measures are insufficient to describe and understand this process and can only provide superficial cues. Quality evaluations by automobile customers are based on their perceptions, emotions, interpretations and expectations. The perceived quality of idling sounds and vibrations is an interesting subject in vehicle acoustics because sounds and vibrations consist of mixtures of stationary and non-stationary signal components. In evaluating automotive sound quality, there arises the need to identify and elicit the relevant attributes, which are the dimensions of the perceived quality.

The aims of this study are the generation, comparison and evaluation of the quality attributes of automotive idle sounds and whole-body vibrations. The identification of the relevant attributes is not a straightforward process. Several elicitation techniques may be used to elicit attributes. All techniques, however, have weaknesses and strengths. In this study, two different techniques were used to elicit verbal descriptors related to the perception and quality of vehicle idling sounds and vibrations. One of the verbal elicitation techniques is a recently developed systematic approach that is based on the free verbalisation technique. The other method is the repertory grid technique (RGT). First, the results of both methodologies were compared, and then the obtained attributes regarding the perception modalities (auditory and tactile) were compared. Finally, the idling sounds and vibrations were evaluated using the derived sets of attributes, and the quality factors were determined.

The remainder of the paper is organised as follows: the elicitation techniques are discussed in Section 2. The elicitation experiments are described in Section 3. Finally, the two semantic differential investigations conducted to evaluate idling sounds and idling vibrations are discussed in Section 4.

## 2 Elicitation methods

There are various direct and indirect methods used to elicit verbal descriptors. The main advantage of the direct methods compared with indirect methods is that the subjects describe their perceptions verbally. These verbal descriptions are very helpful for the experimenter in interpreting the experimental results. In indirect methods, which do not use verbal descriptions from the subjects, the experimenter attempts to identify verbal descriptors and quality dimensions using her/his expertise, which is a very difficult and unpromising process (Silzle, 2006; Wickelmaier, 2005).

All direct elicitation methods have several advantages and disadvantages. It is not possible to state categorically that one method is the best among them. Therefore, it was necessary to select a suitable method for this study. One important criterion is the elicitation of the descriptors using target customers as subjects because experts' knowledge, tastes, interpretations, and expectations may differ strongly from those of the targeted customers (Bech and Zakharov, 2006; Altinsoy and Jekosch, 2012). Therefore, descriptive analysis, quantitative descriptive analysis, or the Delphi method (taxonomy), in which an expert group develops a common language that comprehensively and accurately describes the stimuli features, were not suitable for this study (Murray et al., 2001; Dalkey and Helmer, 1963). In this study, two direct elicitation methods were used: the multi-sequential systematic approach (MSSA), based on the free verbalisation technique, and the RGT. The justification for using two completely different methods lies in approaching problem solving from different perspectives and the possibility for comparison of the results of both methods. When necessary, such comparison allows for a readjustment of the final results. The two elicitation methods are introduced in the following sections.

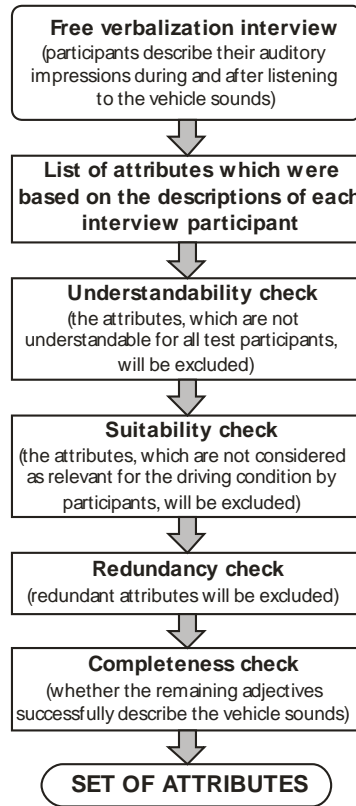
### 2.1 *MSSA based on free verbalisation*

The recently developed systematic approach, which is based on the well-known free verbalisation interview method, is a relatively effective way to determine a common language among customers that appropriately describes vehicle sound quality (Altinsoy and Jekosch, 2012). The aim of this approach is to generate a common set of attributes across all test subjects rather than individual attributes for each subject. The approach consists of five sequential steps: a free verbalisation interview and assessments of the understanding, suitability, redundancy and completeness of the attributes (see Figure 2).

In a free verbalisation interview, participants describe the associated meaning of the stimulus/event regarding their perceptions, their emotions, their experiences and their attitude while performing a task (van Someren et al., 1994). At the end of the *free verbalisation interview*, a list of descriptive attributes is collected from all interview participants. As the verbal descriptors used by the participants vary, in the next step, it is necessary to verify the comprehensibility of these attributes for all participants and so obtain a consensus set of attributes. Another important criterion is the suitability of these attributes for describing the perceived vehicle sound properties. All terms rated less than the maximum suitability value are excluded. However, several of the attributes in the list may have the same meaning. In the next step, attribute redundancies should be checked. Therefore, a semantic differential is conducted using the remained attributes. If two or more attributes were rated similarly, it is possible that they have the similar meaning. A

cluster analysis on the semantic differential data can prove whether those are indeed redundant.

**Figure 2** The MSSA and its steps



Finally, the completeness of the database is evaluated to understand whether remaining attributes successfully describe the stimuli. To accomplish this goal, a similarity experiment is conducted. In the similarity experiment, the sound pairs are presented to the subjects. Subjects rate pair similarity using a quasi-continuous scale. If a subject compares two sounds, the dissimilarity rating of the subject for these sounds is based on the sum of her/his perceived differences with regard to the attributes (for example loudness, booming, etc.). The comparison of the results of the stimulus similarity and semantic differential investigations is then used to assess the completeness of the database. If the database is complete, dissimilarities among sounds should be congruent with the results of the perceived differences between their descriptive terms. This relationship was described in Altinsoy and Jekosch (2012) as follows:

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

where  $\delta_{i,j}$  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 ensures the completeness of the semantic database. After the completeness check, the elicitation process is finished.

One of the advantages of this method is that it can be applied for a large number of stimuli. In the free verbalisation interview, the subjects are not required to compare stimuli with each other. Therefore, the duration of this method is usually shorter than that of other techniques. Recent product sound quality studies claim that experts' knowledge, taste, interpretations, and expectations in the majority of cases strongly differ from those of the targeted customers (Altinsoy and Jekosch, 2012). Another advantage of this method is that the experts' taste, interpretations, and expectations play no role in the analysis of the free verbalisation interview, which includes an assessment of the suitability, understanding, redundancy, and completeness of the data.

## 2.2 *Repertory grid technique*

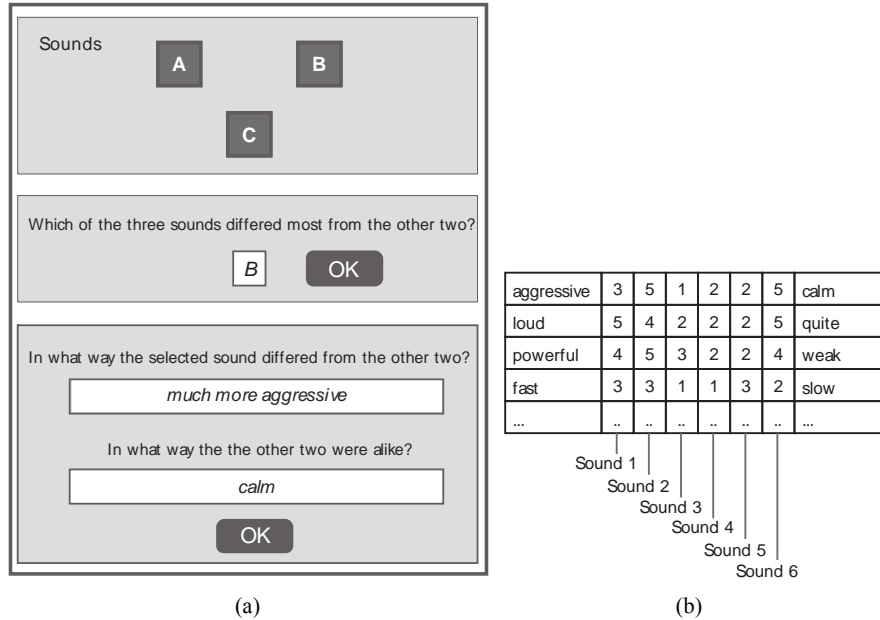
The RGT was originally developed in the 1950s by Kelly (1955) to elicit personal constructs. Over the years, the technique has found widespread applications (Björklund, 2008). Recently, the RGT was used to elicit the auditory attributes of multi-channel sound for the first time (Berg and Rumsey, 2006; Choisel and Wickelmaier, 2006).

In the RGT, the subject is confronted with triads of stimuli and asked to indicate which of the three sounds (or vibrations) differs the most from the other two [Figure 3(a)]. He or she is then asked to describe ways in which two of the stimuli are similar and different from the third. This step results in a list of attributes. Subsequently, a grid is constructed to evaluate the relationships among the stimuli and attributes [Figure 3(b)]. The stimuli form columns, and the elicited attributes form the rows of the grid (a two-way table). In the following step, the subjects provide ratings describing how each stimuli relates to an attribute. Various rating scales and strategies can be used for this evaluation. Finally, the researchers analyse and interpret the grid using statistical data analysis methods such as cluster analysis, PCA and CA.

The advantages of this technique are that it provides a well-defined and structured process to elicit the attributes, it allows subjects to compare stimuli with each other and it makes it possible to elicit the participants' vocabulary rather than using the expert's vocabulary. A disadvantage of RGT is that it presents difficulties with large numbers of stimuli because the number of stimuli comparisons increases immensely, and performing these comparisons takes a long time.

Recently, Parizet et al. (2005, 2007) reported an experiment designed to determine the perceptual dimensions of noise and vibration in cars at idle, using the paradigm of Samoylenko et al. (1996). In this approach, subjects judge the degree of dissimilarity of stimuli pairs and then freely explain the reasons for their judgments. This method is based on stimulus comparison; therefore, it has several similarities with the RGT. The authors found that the pleasantness of noises, the irregularity of noise and vibration stimuli and the amplitude of vibrations are three important axes defining the perceptual space of noise and vibrations, and their results showed that verbalisations can be helpful in understanding this perceptual space.

**Figure 3** The RGT, (a) An example of the graphical user interface for the subject (the purpose of the first step of the RGT is to elicit the verbal descriptors) (b) An example grid: a rating form, which contains the verbal descriptors, will be presented to the subjects (the sound stimuli were then rated by the subject using, for example, a five-point scale)



### 3 Elicitations of attributes for the assessment of vehicle idling sounds and vibrations

Representative vehicle types (e.g., city car, small family car, large family car, executive car, luxury car, sports car and sport utility vehicle) of various brands and with several different motors were selected for this investigation. Sound and whole-body vibration recordings were conducted in 32 cars (16 with diesel engines and 16 with gasoline engines). In the majority of cases, the cold idle condition includes hot idle noise characteristics and other impulsive and non-stationary aspects. Therefore, the cold idle was selected for sound and vibration recording. Vehicle interior sounds were recorded binaurally in the cold idle condition using an artificial head (HEAD acoustics HMS) at the co-driver seat. Simultaneously, whole-body vibrations were recorded using a semi-rigid pad with a triaxial accelerometer (B&K 4322) that was placed between the (driver) seat and the driver. A driver (82 kg) was present during the recordings.

The sound recordings from the 32 cars demonstrate the importance of the large number of idling sound stimuli in this investigation. A preliminary investigation was conducted in which the subjects were asked to evaluate the similarity of the stimuli. The dissimilarity ratings revealed that the stimuli present perceptible differences. Due to the large number of stimuli, the attributes for idle sounds were elicited using the multi-sequential systematic approach. An investigation with the RGT was not possible because of the extraordinarily long test duration that would be required for the 32 sounds. The

analysis of the vibration recordings from the same cars found that only 14 cars have a vibration level that is above the perceptual threshold (Morioka and Griffin, 2008; ISO 2631-2, 1989). Therefore, the attributes for vehicle idling vibrations could be elicited using both methods: the MSSA and RGT.

### *3.1 Investigation of vehicle idling sounds*

A total of 38 subjects (27 males and 11 females) participated in the experiments. All subjects were native German speakers between 21 and 55 years old with normal hearing ability (as determined by testing) and were paid for their participation on an hourly basis. The subjects had no technical background and, thus, no specific knowledge of acoustics or vibrations.

The binaurally recorded sounds of the 32 cars were presented to the subjects through HEAD acoustics HA II.1 headphones using a PEQ IV equaliser. In the training session, several visual aids, including a video of starting a car and idling and a video of a car waiting for a red traffic light to turn green, were used to contextualise the auditory stimuli and to explain the idle condition.

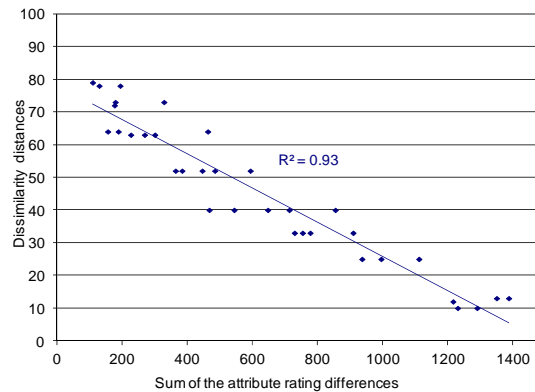
For the elicitation investigation, the MSSA was used, as described in Section 2.1. In the first step of the investigation, the subjects were asked to verbalise their perceptions and impressions during and after listening to the idling sounds. At the end of this step, 376 verbal descriptors were collected. The number of verbal descriptors used by a given subject varied from 118 to 278. The comprehensibility of the verbal descriptors for all subjects is an important criterion in eliciting the common descriptive language of the subjects. In the following step, the subjects were asked which of the 376 verbal descriptors they understood and which they did not. At the end of this evaluation, the 88 terms that were identified by one or more subjects as not understandable or as unclear were excluded. The subjects then evaluated the suitability of the remaining attributes for describing the idling sounds using a quasi-continuous Rohrmann graphical scale ranging from 'not suitable' to 'extremely suitable' [a detailed description of the scale can be found in Altinsoy and Jekosch (2012)]. All attributes that were rated less than 'very suitable' (75% of the maximum suitability rating) were excluded. Several of the remaining attributes were antonym pairs. Therefore, one pole of each antonym pair was excluded from the list. Redundant attributes with similar meanings were then excluded from the list; only the terms receiving the maximum suitability ratings among the redundant attributes were retained. In the following step, a semantic differential investigation (see Section 4) and a dissimilarity investigation were conducted. The dissimilarity distance between the sounds and the sum of the perceived differences between their descriptive terms were compared to verify the completeness of the database. A linear regression analysis was conducted to evaluate the relationship, yielding a correlation coefficient of  $r^2 = 0.93$  (Figure 4).

After the successful conclusion of the completeness check, the elicitation process was over. The attributes were translated by two bilingual (English – German) language specialists and discussed with the authors. The attributes, listed in Table 1, describe the timbre of the idle sound (e.g., low or high frequency), general product features (e.g., fuel-efficient, gasoline, or new model), operational condition (e.g., over-revved), signal characteristics (e.g., continuous) and emotions (e.g., stressful or arousing). There are also onomatopoeia-based sound descriptors (e.g., buzzing and humming) and comfort descriptors (e.g., comfortable). Subjects used the term *vibration* to describe the



modulation of the sound stimuli. As noted in the interviews, the subjects were not familiar with the term *modulation*.

**Figure 4** The similarity ratings regression line (0 = similar; 100 = extremely dissimilar) and the sums of the attribute rating differences (see online version for colours)



**Table 1** The set of interior vehicle idling sound attributes

1	Aggressive (aggressive)	18	Moderate (dezent) → showy
2	Annoying (lästig)	19	Muffled (gedämpft)
3	Arousing (weckend)	20	New model (neues Modell)
4	Booming (dröhnen)	21	Ordinary (gewöhnlich) → unique
5	Buzzing (summen)	22	High overall quality (hohe Gesamtqualität)
6	Clatter (rattern)	23	Pleasant (angenehm)
7	Comfortable (komfortable)	24	Purring (schnurren)
8	Continuous (kontinuierlich)	25	Quiet (leise) → loud
9	Effortless (müheless) → strained	26	Rattling (rasseln)
10	Fuel-efficient (sparsam)	27	Rickety (klapprig)
11	Gasoline (Benziner) → diesel	28	Roaring (röhren)
12	Howling (heulen)	29	Smooth (laufruhig) → over-revved
13	Humming (brummen)	30	Sporty (sportlich)
14	Knocking (hämmern)	31	Squeaking (quietschen)
15	Low 'frequency' (tief) → high	32	Stressful (stressig)
16	Low vibration (vibrationsarm)	33	Weak (schwach) → powerful
17	Luxurious (luxuriös)	34	Whistling (pfeifen)

Bipolar adjective pairs are typically used in semantic differential investigations. However, in our case, several attributes, particularly the onomatopoeic attributes, have no clear opposites. In a previous study, it was found that the results were very similar when sounds were evaluated using either a unipolar scale, e.g., pleasantness, or a bipolar scale, e.g., pleasant-unpleasant (Altinsoy and Jekosch, 2012). Therefore, a unipolar scale was used in this study when the attribute had a clear meaning; otherwise, a bipolar scale was

used whenever possible. The opposite poles of several attributes are provided in the list in Table 1, indicated by arrows.

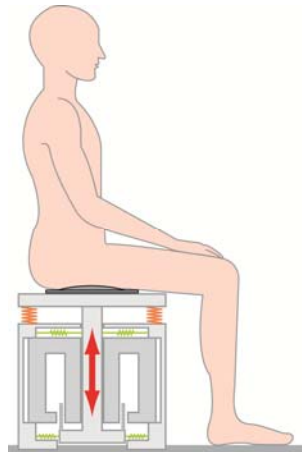
### 3.2 *Investigations of vehicle idling vibrations*

#### 3.2.1 *MSSA investigation*

A total of 32 subjects (24 males and eight females) participated in the experiments. None of the subjects participated in the previous noise investigation (Section 3.1). All the subjects were native German speakers between 18 and 52 years old. Their masses varied from 51 kg to 97 kg (mean: 76 kg). The subjects had no technical background and, thus, no specific knowledge of vibrations or acoustics. All subjects indicated that they had no spinal damage, and they were paid for their participation on an hourly basis.

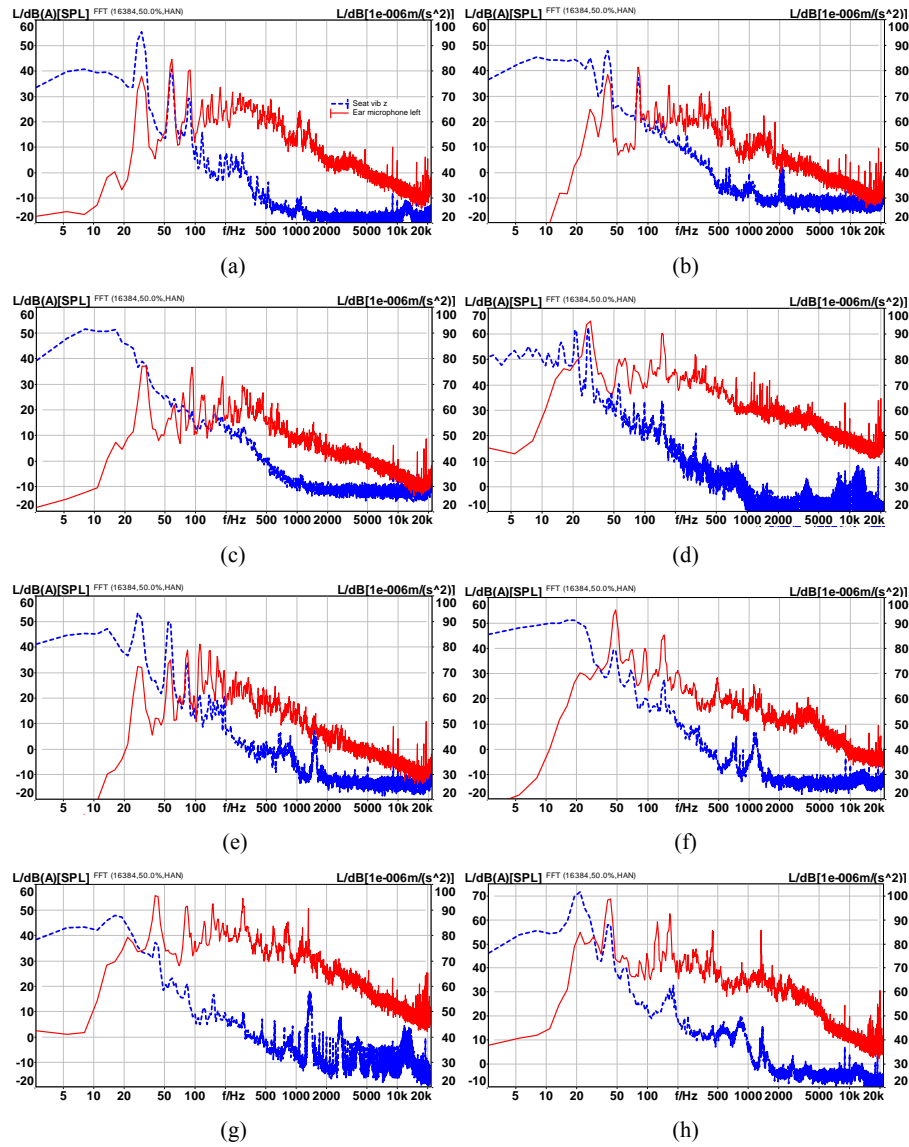
The experimental setup of this investigation was the same as in our previous experiment (Altinsoy and Merchel, 2010). Whole-body vibrations were reproduced using an electro-dynamic vibration seat (Figure 5). The seat had a flat, hard wooden surface with no backrest and a stationary footrest (460 mm × 460 mm). The system is capable of producing vertical vibrations in a frequency range from 5 Hz to 1 kHz. The individual properties of the person being tested, such as weight and the amount of adipose tissue, play a role in the frequency response of the seat (Altinsoy and Merchel, 2010). The transfer characteristic of the shaker when loaded with a seated person, called the body-related transfer function (BRTF), was measured using a semi-rigid pad with a triaxial accelerometer. All stimuli were adjusted for the transfer characteristic of the seat in the vertical direction using inverse filters in MATLAB. The subjects wore closed dynamic headphones (Sennheiser HDA 200) that have sound isolation levels of 15 dB at 125 Hz, 22 dB at 500 Hz, and 29 dB at 1 kHz. In addition to this passive attenuation, a pink noise was supplied at 50 dB(A) to acoustically mask the noises emitted by the shaker when it generated the signal.

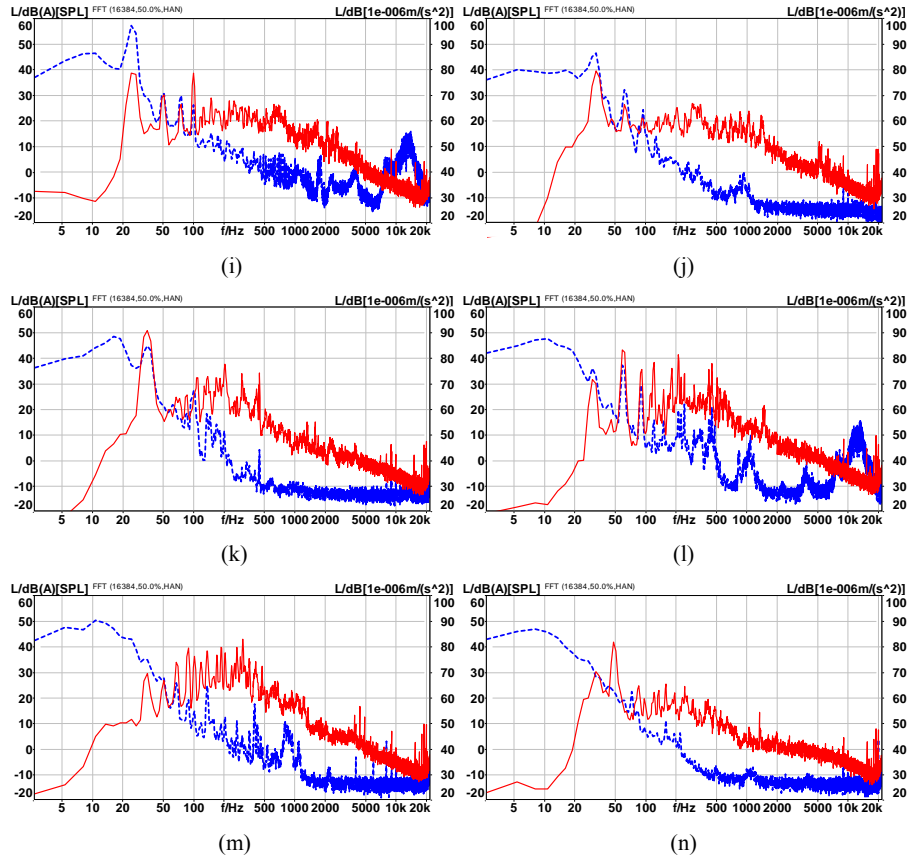
**Figure 5** The experimental setup for the electrodynamic shaker with a seated subject (see online version for colours)



The vertical vibrations of 14 cars were presented to the subjects through the vibration seat. Both the vertical vibration and the interior noise power spectra of the vehicles are presented in Figure 6. The spectra were obtained with 16,384 FFT points. In the majority of the spectra, the presence of engine orders can be observed in both the vibration and noise recordings. Engine orders were more obvious in the diesel vehicles. In the frequency range above 100 Hz, the level of vibration was below the perceptual threshold value.

**Figure 6** Interior sound (solid line) and vibration (dashed line) spectra of the stimuli (see online version for colours)



**Figure 6** Interior sound (solid line) and vibration (dashed line) spectra of the stimuli (continued)  
(see online version for colours)

The general procedure and the steps of the investigation were the same as in the auditory elicitation experiment. In the training phase, which required approximately 15 minutes, all participants were first presented with different stimulus combinations from across the full stimulus range, and they were then familiarised with the idle driving condition using the same visual materials as in the auditory investigation. The duration of each stimulus was 5 seconds. This duration allowed the subjects to form an overall opinion on the idle stimuli without becoming bored by remaining within the time span of human short-term memory (Baddeley, 1997). The subjects were allowed to experience the stimuli as much as they desired. The stimuli were presented in random order.

First, the subjects verbalised their impressions during and after exposure to the whole-body vibrations. This step resulted in a list of 63 descriptive attributes. The number of verbal descriptors used by a subject varied from 15 to 49. After the understanding and suitability checks, the number of attributes was reduced to 38. Single poles of the antonym pairs and the redundant attributes were then excluded from the list. The completeness check of the remaining attributes (22) yielded a correlation coefficient of 0.91. The attributes were again translated by the two bilingual language specialists and

discussed with the authors. The majority of the attributes are signal-related terms (Table 2).

**Table 2** The set of interior vehicle idling vibration attributes elicited using the MSSA method.

1	Aggressive (aggressive)	12	Jerking (rumpelnd)
2	Annoying (lästig)	13	Pleasant (angenehm)
3	Arousing (weckend)	14	Rattling (rasselnd)
4	Booming (wummernd)	15	Regular (regelmäßig)
5	Bumpy (holprig)	16	Rough (rau)
6	Buzzing (summend)	17	Rumbling (polternd)
7	Clatter (ratternd)	18	Shaky (zittrig)
8	High frequency (hochfrequent)	19	Strong (stark)
9	High vibration (vibrierend)	20	Uncomfortable (unbequem)
10	Hitting (schlagend)	21	Uniform (gleichmäßig)
11	Humming (brummend)	22	Wavy (wellig)

The participants used the terms *humming*, *rough*, *wavy*, *bumpy*, and *clatter* particularly for the vibration stimuli a, d, e, and h (Figure 6), which are characterised by dominant spectral components at engine orders. Modulation frequency was observed to play a role in the selection of attributes, as did the frequency spectrum of the stimuli. The terms *shaky*, *buzzing* and *high* were used to describe the vibration stimuli a, b, e, which contain several perceptible frequency components higher than 40 Hz. The stimuli l and b, which reflect non-stationary car-shaking problems, were described using the attributes *jerking*, *clatter*, *hitting*, and *annoying*. The stimuli m and n, which do not exhibit dominant spectral components at different engine orders but instead consist of broad-band vibrations from 10 Hz to 50 Hz, were described using the attributes *wavy* and *rumbling*. The temporal properties of such types of stimuli may play a significant role in the selected attributes.

### 3.2.2 RGT investigation

A total of 28 subjects (19 males and nine females) participated in the investigation; none participated in the previous investigations. All subjects were native German speakers between 20 and 56 years old, with masses varying from 57 kg to 95 kg (mean: 72 kg). The subjects had no technical background and, thus, no specific knowledge of vibrations or acoustics. All subjects indicated that they had no spinal damage, and they were paid for their participation on an hourly basis.

The experimental setup and the stimuli were the same as in the previous investigation. A MATLAB graphical user interface (GUI) was developed for the evaluation of the vibrations. Each subject was presented with triads of vibration stimuli and asked to indicate which of the three vibrations differed most from the other two. She/he was then asked to explain the ways in which two of the stimuli were alike and different from the third. The subjects were allowed to play the stimuli as much as they wanted. The stimuli triads were presented in random order. At the end of this part of the investigation, 18 attributes were identified to describe the idling vibrations. The intensity (strength) of the vibration stimuli was the parameter most often used and named by the subjects during

the comparison exercise. Three of the subjects used only intensity-related terms such as *strong* or *weak* to compare the triads. *Annoying* and *unpleasant* were also often used verbal descriptions. Seven of the subjects used not only intensity- but also comfort-related terms. The attributes that describe the characteristics of the signal were generally seldom used. It was decided to conduct the rating part of the RGT investigation as a semantic differential experiment. The resulting attributes are listed in Table 3.

**Table 3** The set of interior vehicle idling vibration attributes elicited using the RGT technique

1	Aggressive (aggressive)	10	Rough (grob, rau)
2	Annoying (lästig)	11	Rumbling (polternd)
3	Booming (wummernd)	12	Shaky (zittrig)
4	Bumpy (holprig)	13	Slow (langsam)
5	Clatter (ratternd)	14	Strong (stark)
6	Hammering (hämmernd)	15	Thunderous (donnernd)
7	High frequency (hochfrequent)	16	Uncomfortable (unbequem)
8	Hitting (schlagend)	17	Uniform (gleichmäßig)
9	Rattling (rasselnd)	18	Wavy (wellig)

### 3.3 Discussion

The elicitation of the auditory stimuli resulted in 34 attributes. The MMSA investigation for the vibration stimuli resulted in 22 attributes, and the RGT investigation for the vibration stimuli resulted in 18 attributes. The subjects used more signal-related and emotional attributes to describe the idling sounds than they did for the idling vibrations. This observation is in line with the results of Parizet et al. (2005, 2007). A likely reason for this difference is the limited frequency range of the idling vibrations (up to 100 Hz) in comparison with the broader frequency range of the idling sounds (up to 2–5 kHz). Another reason is that people may generally have a limited vocabulary to describe such vibrations (Altinsoy, 2011). Therefore, the subjects may have used several auditory descriptors to describe the vibration events, e.g., buzzing or booming. However, the same phenomenon is also known in the audio field (Haverkamp, 2011). Visual terms such as brightness, brilliance or colour are often used to describe auditory events. Intensive research has been performed on auditory-visual synaesthesia (Ward et al., 2006). In this investigation, the subjects did not claim to have auditory-tactile synaesthesia.

In the MMSA investigation of the idling vibration, more attributes describing the signal-related aspects were collected in comparison with the RGT investigation. Similar tendencies were also observed in another auditory assessment study (Berg and Rumsey, 2006). It is possible that the direct comparison of the stimuli makes it easier for the subjects to cope with the elicitation investigation; however, the subjects tended to use the most obvious parameters, such as intensity or comfort, for the comparison of the stimuli. Sophisticated signal-related terms were less frequently expressed. The instructions given to the subjects also play a role in this issue. Berg and Rumsey reported that subjects became more focused and used more signal-related terms when they received additional instructions. It is possible that forcing the subject to use not only intensity- or comfort-related terms but also other terms may improve the results of such investigations.

As the attributes that were elicited in both investigations did not differ significantly, the elicited attributes from the MMSA and RGT investigations were combined.

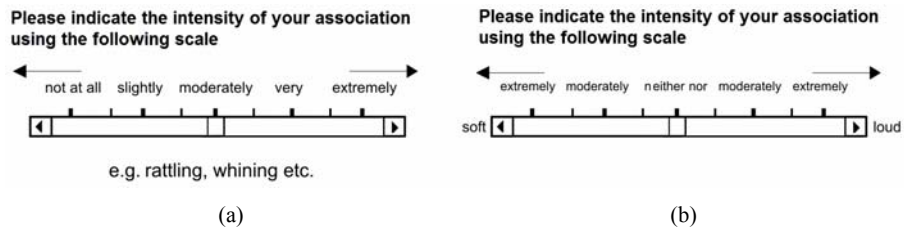
## 4 Evaluation of vehicle idling sounds and vibrations

Using the elicited attributes described in Section 4, two semantic differential investigations were conducted separately for the idling sounds and idling vibrations. The aim of these investigations was to determine the dimensions of the vehicle idling sound and the vibration quality.

### 4.1 Evaluation of vehicle idling sounds through a semantic differential investigation

The setup, stimuli and subjects were the same as in the previous experiment described in Section 3.1. The stimuli were presented in random order. The questionnaire contained a list of thirty-four adjectives (Table 1). The subjects indicated the intensity of their associations on a quasi-continuous scale, for which Rohrman (1978) has tested the equidistance of neighbouring categories (Figure 7). This unnumbered scale consisted of a horizontal slider that was marked with verbal anchors describing different intensities (not at all, slightly, moderately, very, and extremely). The length of the slider was 100 mm, with a resolution of 1 mm. The score on this scale was equal to the distance (mm) of the bar from the left end. A GUI was implemented for the evaluation experiments in MATLAB (Figure 7).

**Figure 7** The Rohrman scale (a) for the terms without an antonym and (b) for the terms with antonyms



A factor analysis was conducted on the dataset using the promax rotation. The results of the factor analysis of the semantic differential led to four independent factors that explained 93% of the variance (Table 4). The adjectives that have loadings with a factor higher than 0.8 are listed in the categories of this factor. The first factor was termed *comfort* because the majority of the comfort- and emotion-related terms are found in this factor group. This factor explains almost half of the variance, indicating that emotion-related terms are very important for the quality evaluation of idle sounds. The second factor was called *high quality* (or *failure*), the third was called *power* and the fourth was called *high frequency*.

**Table 4** Factor analysis results for the idling sounds

<i>Factor number</i>	<i>Adjectives</i>	<i>% variance</i>
Factor 1 'comfort'	Pleasant, comfortable, aggressive, annoying, strained, loud, booming, roaring, new model, moderate, over-revved	48
Factor 2 'failure – high quality'	Luxurious, rickety, rattling, clattering, diesel, unique, high-vibration, buzzing	25
Factor 3 'power'	Powerful, humming, booming, roaring, showy, high vibration	17
Factor 4 'high frequency'	High frequency, whistling, squeaking	3

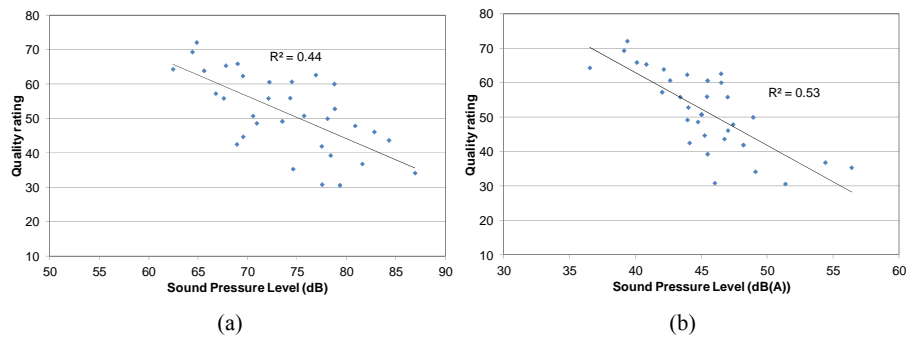
These results confirm that the quality evaluation of the vehicle idling sounds is a complex process. In addition to intensity-dependent attributes, other signal-related terms, e.g., booming, roaring, rattling, clatter, frequency character, whistling, and emotional aspects, also play a role in this process. In signal-related terms, engine-order-related frequency components at low frequencies, which cause humming, booming, etc., should be taken into account for the analysis. This observation is in line with the results of Lee (2006). However, not only the sound levels but also their modulations are important. Terms such as 'diesel' and 'vibration' can be described using the modulation properties at high frequencies. A regression analysis between SPL in dB and dB(A) and the quality judgments for the 32 vehicle idling sounds resulted in correlation coefficients of  $r^2 = 0.44$  and  $r^2 = 0.53$ , respectively [see Figures (8)a and 8(b)]. The results of the elicitation experiments showed that not only intensity related terms but also signal-based attributes in terms of spectral and temporal properties play important roles in the perception of idle sounds. The coefficient of determination scores can be improved using the psychoacoustical parameters such as loudness, sharpness (which is important in characterising the influence of high frequencies), roughness and fluctuation strength (the last two are important to characterise the modulation-based attributes, e.g., humming or booming) and relative approach [which is able to detect rapid time varying signal structures (e.g., diesel knocking)]. An index was developed to account for the relationship between the quality ratings and the calculated psychoacoustic parameters. In this study, the Zwicker model was used for the calculation of the loudness (ISO532B), the Aures models were used for the calculation of sharpness and roughness (Aures, 1985a, 1985b), the Terhardt model was used for the calculation of the fluctuation strength (Terhardt, 1968), and Genuit/Sottek model was used to calculate the metric 'relative approach' (Genuit, 1996; Sottek and Genuit, 2005). A comparison of the psychoacoustic parameters of the 32 idle sounds and their quality ratings showed that loudness and sharpness are almost equally important for the quality judgments. Although the roughness and the fluctuation strength play an important role on the quality evaluation of the idle sounds, their importance is not as great as the loudness and sharpness parameters. Therefore, the weightings for roughness and the fluctuation strength are approximately half of the weightings for the loudness and the sharpness. Considering the differences in the numerical values of the loudness, the sharpness, the roughness, the fluctuation strength, and the relative approach (average loudness of the 32 idle sounds, 4.3 sone; average sharpness, 0.65 acum; average roughness, 0.22 asper; average fluctuation strength, 0.19 vacil; and average relative approach: 3.1 cPa), the index was defined using the following formula:



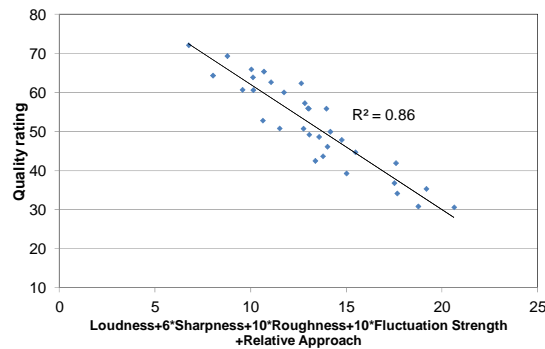
$$QI = L + 6 * S + 10 * R + 10 * FS + RA \tag{2}$$

where  $L$  is the loudness according to ISO532B,  $S$  is the sharpness according to Aures,  $R$  is the roughness according to Aures,  $FS$  is the fluctuation strength according to Terhardt, and  $RA$  is the relative approach according to Genuit and Sottek. A regression analysis between the developed index and quality ratings resulted in a correlation coefficient of  $r^2 = 0.86$  (Figure 9). To achieve a better correlation, complex parameters such as aggressiveness, powerfulness, luxurious and pleasantness must also be modelled. If such kind of emotional attributes should be modelled, the relationship between the product and customer play an important role. However, the models of emotional attributes are often not a simple linear combination of different signal-related attributes or psycho-acoustical parameters. In most cases, these signal-related attributes interact with each other in a complex way to evoke an emotional reaction. The results of this study were examined to obtain some knowledge about the relationship between the emotional parameters (aggressive and powerful) and other signal-related attributes.

**Figure 8** Results of regression analyses between (a) the quality judgments and SPLs in dB and (b) the quality judgments and SPLs in dB(A) (see online version for colours)

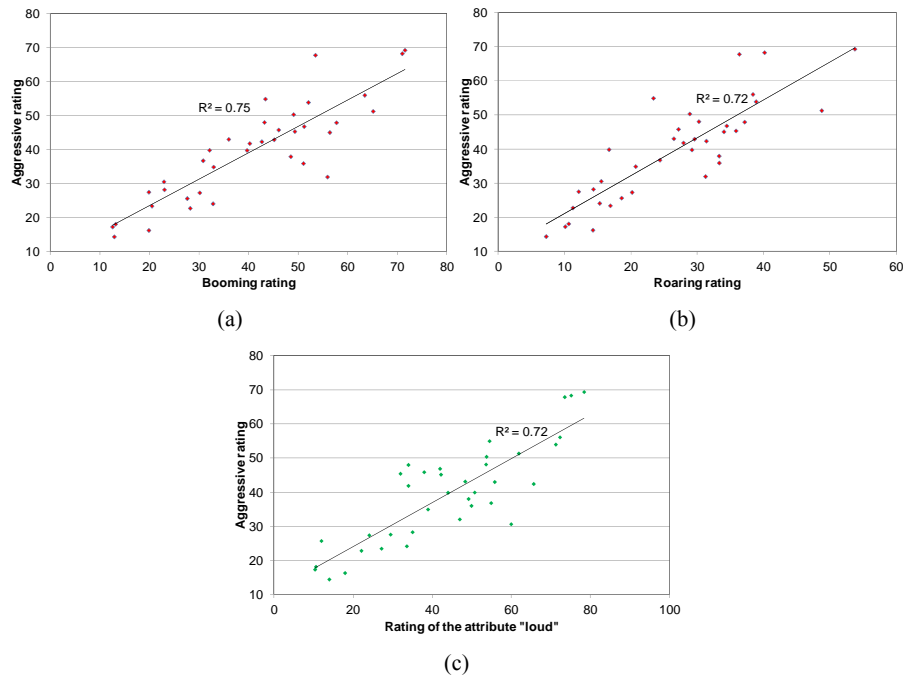


**Figure 9** Results of a regression analysis between the quality judgments and the weighted combinations of the psychoacoustic properties: loudness, sharpness, roughness, fluctuation strength, and relative approach (see online version for colours)



The results of the attribute ratings show that the emotional term ‘aggressive’ is a complex variable that is dependent on the booming, the hum, the clatter, the roaring, the knocking, and the loudness. In particular, there is a high correlation between the aggressive ratings and the booming, the loud and the roaring ratings. A regression analysis between the ratings for aggressive and booming resulted in a correlation coefficient of  $r^2 = 0.75$ , the ratings for aggressive and roaring resulted in a correlation coefficient of  $r^2 = 0.72$ , and the ratings for aggressive and the attribute loud resulted in correlation coefficient of  $r^2 = 0.72$  (Figure 10). Other terms, e.g., the hum ( $r^2 = 0.54$ ), the clatter ( $r^2 = 0.51$ ), and the knocking ( $r^2 = 0.61$ ) interact with each other and contribute to the aggressive perception. Particularly, high levels of each term result in high aggressive ratings. When two or more attributes are rated higher than the scale point ‘moderately’, synergistic effects arise regarding the aggressive judgment.

**Figure 10** Results of regression analyses between (a) the aggressive judgments and the booming judgments, (b) the aggressive judgments and the roaring judgments, and (c) the aggressive judgments and the loud judgments (see online version for colours)



The term ‘powerful’ is also dependent on the loudness, the booming, the hum and the roaring. Additionally the frequency (high-low) plays a role on the powerfulness perception. A regression analysis between the ratings of powerful and booming resulted in correlation coefficient of  $r^2 = 0.86$  and the ratings of powerful and roaring resulted in correlation coefficient of  $r^2 = 0.80$ . These results suggest that the powerfulness is highly dependent on the engine order-based frequency components and their levels. Particularly, high level of the loudness ( $r^2 = 0.56$ ), the low (frequency) ( $r^2 = 0.62$ ) results with a high powerfulness rating.

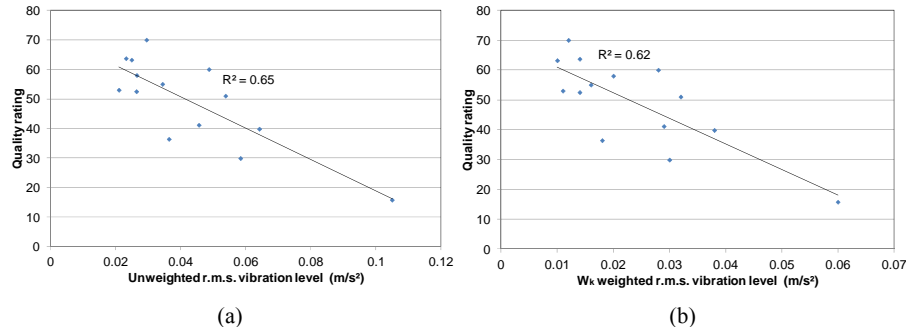
#### 4.2 Evaluation of vehicle idling vibrations through a semantic differential investigation

The setup, stimuli and subjects were the same as in the previous experiment described in Section 3.2. The stimuli were presented in random order. The semantic differential investigation consisted of the 22 attributes that were elicited in the MSSA investigation and two additional attributes, slow and thunderous, elicited in the RGT investigation. The same quasi-continuous scales used in the auditory investigation were used for this evaluation. A factor analysis was conducted on the dataset using the promax rotation. The results of the factor analysis of the semantic differential led to three independent factors that explained 89% of the variance (Table 5).

**Table 5** Factor analysis results for the idling vibrations

Factor number	Adjectives	% variance
Factor 1 'comfort'	Pleasant, aggressive, annoying, strong, humming, rattling, clatter, rough	43
Factor 2 'regularity-impulsiveness'	Uniform, regular, hammering, bumpy, hitting, rumbling, jerking	35
Factor 3 'tonality'	Humming, rough, high frequency	11

**Figure 11** Results of regression analysis between (a) the quality ratings and the unweighted r.m.s. acceleration amplitude of the vibration stimuli and (b) the quality ratings and the wk weighted r.m.s. acceleration amplitude of the vibration stimuli (see online version for colours)



The comfort- and emotion-related terms (factor 1) explain almost half of the variance similar to the auditory investigation. The results show that in addition to the level that was described with the attribute strong, other signal-related terms such as humming, clatter and rough are important for the vibration evaluation. Strong, humming, rough, and rattling vibrations caused unpleasant and aggressive emotions. Regularity-based terms, which are grouped in factor 2, play a significant role in this driving condition. The impulsive vibrations caused by irregular combustion, as described in Section 1, were described by subjects using the attributes irregular, jerking, hitting, clatter, and hammering and together with the regularity-based terms explain 35% of the variance. The attributes that were used by subjects to describe the modulated vibration signal, such as rough, bumpy, humming, also play important roles the perception of quality. A regression analysis between the level [unweighted r.m.s. and Wk weighted r.m.s.

according to ISO 2631-1 (1997)] and the quality judgments revealed that there is no simple linear description of this relationship (Figure 11). This result is very similar to that obtained in the auditory investigation. The quality of idle vibrations cannot be sufficiently described using only the vibration level. This result is very similar to that obtained in the auditory investigation.

### 4.3 Discussion

The comparison of the results of the semantic differential investigations for idling sounds and vibrations showed that the quality evaluation depended on various parameters. In both cases, the level is an important parameter but does not completely describe the signal complexity; rather, the level describes only a small part of the complexity. Signal-related terms in time and frequency play roles in both cases. The number of such terms is greater in the sound case than in the vibration case, possibly due to the limited frequency range of the vibrations. It is also possible that the limited vocabulary of the subjects plays a role here. There have been successful attempts to model signal-related terms in several prior studies (Genuit, 1996; Sottek et al., 2005; Sellerbeck et al., 2007). Signal irregularity is an important comfort criterion, particularly for vibration, but also for sound signals. This observation is in line with the results of Parizet et al. (2005). However, in addition to their irregularity, the modulation of the signals is also an important criterion. The level of engine-order-based frequency components and their interactions should be considered in such modelling.

It is also obvious from our results that emotional terms primarily belong in the first factor group, which accounts for an important part of the variance. These terms should be considered for the characterisation of idling NVH performance. Therefore, it is necessary to develop models that describe the relationships between these emotional terms and signal parameters (Tajadura-Jiménez, 2008; Genell et al., 2010). The results of the auditory semantic differential investigation indicate that there is a strong relationship between the emotional term aggressive and the booming, humming, clattering, roaring, knocking, and loud sounds. Therefore, strong excitation at main engine orders that causes booming, humming or roaring can result the perception of aggressive emotions. The combination of booming or roaring with high loudness creates synergistic effects and induces high aggressivity. Additionally, the impulsiveness of the signal, which was reported by subjects as knocking, can also induce aggressive emotions. Similar tendencies were observed for the idle vibrations. Strong excitation at main engine orders that causes, humming, rough, and rattling vibrations can induce unpleasant and aggressive emotions.

## 5 Conclusions

In this study, the attributes that play roles in the quality evaluation of vehicle idling sounds and vibrations were elicited, compared, and evaluated. In contrast to previous investigations (Lee, 2006), the results of this study showed that the quality of both idle sounds and idle vibrations have multidimensional, complex characters.

A total of 34 attributes were elicited for the sounds. These attributes can be divided into categories referring the timbre of the idle sound (e.g., low or high frequency), general product features (e.g., fuel-efficient, gasoline, or new model), operational

condition (e.g., over-revved), signal characteristics (e.g., continuous) and emotions (e.g., stressful or arousing). There were also onomatopoeia-based sound descriptors (e.g., buzzing or humming) and comfort descriptors (e.g., comfortable). Several of the technical terms used by NVH experts, e.g., diesel knocking/impulsiveness, were not known to the subjects, representing average customers who were unaware of such technical or specific signal-analysis terms. Average customers used the term 'vibrating' to characterise the modulations, which can also be caused by diesel knocking. However, several of the technical terms used by NVH experts, e.g., rattling or humming, were also used by the participants. Either these technical terms have origins in our daily language (for example as onomatopoeias) or they are integrated into it.

Tactile quality descriptors for idling whole-body vibrations were elicited to this large extent for the first time in this study. A total of 22 attributes were elicited for the vibrations. The terms humming, rough, wavy, bumpy, and clatter were used particularly for the vibration stimuli, which are characterised by dominant spectral components at engine orders. Non-stationary car-shaking problems were described using the attributes jerking, clatter, hitting, and annoying. The attributes wavy and rumbling were used to characterise broad-band vibration signals between 10 Hz and 50 Hz. Several emotional terms, e.g., aggressive, arousing, etc., were also used by the participants to characterise the idle vibrations.

As expected, the number of auditory terms elicited was higher than the number of tactile terms. One of the reasons for this difference is the limited frequency range of the vibrations. The results reveal that the adjectives provided for sounds and whole-body vibrations have several similarities. One possible reason for their similarity is that these sounds and vibrations are coupled by physical laws, and there is therefore a strong correlation between the frequency of the sound and the frequency of the vibration.

The results of the semantic differential investigations show that descriptive attributes in terms of level, such as loud or strong; signal-based attributes in terms of spectrum and temporal properties, such as uniform, regular, hammering, bumpy, hitting, rumbling, or jerking; and comfort- and emotion-based attributes, e.g., pleasantness or aggressiveness, are required to characterise the idling NVH performance. The level of the stimuli alone cannot explain the overall idle quality, particularly because modulations at low and high frequencies and non-stationary impulsive signal properties play similarly important roles in the quality evaluations. Therefore, an index based on psychoacoustic metrics such as loudness according to ISO532B, sharpness according to Aures, roughness according to Aures, fluctuation strength according to Terhardt, and relative approach according to Genuit and Sottek, can be used to predict the overall quality of the idle sound.

The factor analysis of the semantic differential data showed that emotion-related terms explain almost half of the variance in both cases (auditory and tactile). These emotional terms, such as aggressive or pleasant, are related to certain signal properties; however, in the majority of cases, there is no simple linear relationship between the signal and the perception, with several exceptions. For example, there is a relationship between the term aggressive and the sound attributes booming, hum, clatter, roaring, knocking, and loudness. The relationships of aggressive to booming, loudness and roaring are roughly linear, whereas the relations with the other properties are more complex in character.

In this study, the two sensory modalities (auditory and tactile) were separately investigated. The next step of this study will include a multimodal quality experiment using the elicited unimodal and multimodal attributes from this study. When the two

modalities are combined, the resulting multimodal percept may be a weaker or stronger percept (i.e., ‘additive or subtractive’ interactions; Västfjäll, 2003; Parizet et al., 2004; Genuit and Fiebig, 2007) or an altogether different percept, and of course, it is also possible that one modality may dominate overall assessments related to the physical/perceptual ability of the subject, the nature of the task, or personal preference (McGee, 2002).

Two techniques, MSSA and RGT, were used to generate semantic differentials for the vehicle sounds. Although both techniques delivered comparable results, more attributes were elicited using the MSSA. Both techniques have strengths and weaknesses. In future experiments, several aspects of the RGT such as additional ‘forcing’ instructions and other analysis and interpretation techniques should be investigated.

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