Mapping the Sensory-Perceptual Space of Vibration for User-Centered Intuitive Tactile Design

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***Abstract*—In vibrotactile design, it can be beneficial to communicate with potential users about the desired properties of a product. However, such users' expectations would need to be translated into physical vibration parameters. In everyday life, humans are frequently exposed to seat vibration. Humans have learned to intuitively associate specific labels (e.g., "tingling") with specific vibrations. Thus, the aim of this article is to identify the most common sensory-perceptual attributes and their relationships to vibration parameters. First, we generalized everyday-life seat vibration into sinusoidal, amplitude-modulated sinusoidal, white Gaussian noise and impulse-like vibrations. Subsequently, the (peak) level, (center/carrier) frequency, bandwidth, modulation frequency and exponential decay rate parameters of these vibrations were systematically varied depending on the signal type. A free association task was conducted to reveal the most common sensory-perceptual attributes for each vibration. After aggregating similar attributes, the 21 most frequently occurring attributes were utilized in a second experiment to rate their suitability for describing each vibration stimulus. Principal component analysis guided the selection of six attribute groups, which can be represented by "up and down," "tingling," "weak," "repetitive," "uniform" and "fading." The observed relationships between vibration parameters and attribute ratings are suitable for future model building.**

***Index Terms*—Haptic I/O, human factors, human information processing, haptic perception, vibrotactile feedback, user-centered design.**

I. Introduction

With increasing computational power, simulations have become an integral part of product design and development to increase efficiency and reduce costs, e.g., in the vehicle industry. In the physical domain, it is possible to predict structural vibrations with increasingly accurate models, reducing the reliance on experience. However, in the perceptual domain, such models are not available to predict tactile customer perception and, ultimately, perceived quality. Thus, incremental improvements of successive prototypes are required, which have to be evaluated in perceptual studies.

Tactile design strategies aim to ensure that vibration is judged favorably or that a message conveyed via vibration is intuitively understood. One of the major factors influencing perceived quality is user expectations [1]. While interacting with a product, users will compare their perception to their expectations of the product in a given application context according to all relevant perceptual properties. Similarly, intuitive vibrotactile design attempts to minimize the required training by matching the perceptual properties elicited by vibration to the properties expected for an intended message. Therefore, product designers are often interested in the judgments of potential future users to assess the agreement between elicited perceptual properties and expectations. However, expectations mostly play an implicit role when users rate whether the presented vibration matches the expectations of the product. Not knowing the expected perceptual properties and elicited perceptual properties limits the designer to trial-and-error strategies to define optimal physical vibration parameters. Thus, assessing expected tactile perceptual properties explicitly and subsequently deriving optimal vibration parameters that will elicit these perceptual properties might be a more efficient design strategy. Three obstacles need to be overcome to achieve this goal.

First, laypersons cannot describe the desired physical product properties, i.e., vibration directly in the form of the level or frequency because they lack expert engineering knowledge. Instead, they usually come up with associations that are elicited by vibration, e.g., "tingling." Thus, the vocabulary of perceptual attributes actually utilized by laypersons for communicating about vibration needs to be identified. The range of physical vibration properties of the presented stimuli needs to be representative of everyday-life exposure.

Second, qualitative communication about user perception in the form of unstructured user interviews is difficult to unify into a set of compact perceptual features, especially due to the many synonyms and antonyms contained in natural language. Therefore, a standardized way of explicitly communicating with users in an efficient and sufficient manner regarding the sensory tactile perceptual space is required. Such a standardized perceptual attribute vocabulary, i.e., a tactile design language [2], does not yet exist. This vocabulary would enable design engineers to rely on potential product users for the

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specifications of the required tactile perceptual properties in the form of quantitative rating profiles. This is the prerequisite for assessing perceptual features expected to be elicited by the vibration of a future product.

Third, physical vibration parameters need to be derived from such perceptual specifications, i.e., attribute rating profiles. For a given vibration characterized by its physical vibration parameters, it is relatively easy to obtain such rating profiles from perceptual studies. However, the inverse problem of obtaining vibration parameters from given, arbitrary rating profiles is far more difficult. To avoid the use of trial-and-error strategies to solve this problem, libraries or databases of limited vibration items with discrete mappings to their elicited sensations are sometimes utilized [3]. Given an arbitrary rating profile, the designer is limited to choosing an item with an approximately similar rating profile. The deviation from the ideal rating profile is likely to negatively affect the user's judgments. Instead of increasing the number of items in the database, it would be more efficient to identify continuous mappings, i.e., systematic relationships between vibration parameters, e.g., level or frequency, and tactile perceptual properties, e.g., "tingling." Characterizing the relationships of all attributes of the potential design language could eventually enable the creation of models. These models might facilitate a much more flexible translation from freely definable perceptual attribute ratings to optimal physical parameter values. For auditory perception, models exist for the analysis of perceptual attributes, e.g., loudness or roughness [4]. For vibrotactile perception models for predicting sensory tactile perceptual attribute ratings elicited by vibration or for synthesizing vibration based on them, such ratings are not available for the most relevant of these attributes.

This paper will progress towards a more efficient tactile design strategy by attempting to establish a tactile design language as a standardized way of explicitly and quantitatively communicating about the sensory tactile perceptual properties of seat vibration, as frequently occurring in vehicles, in a layperson-understandable way. Furthermore, this paper will demonstrate that the elements of this design language show systematic relationships to characteristic spectral and temporal vibration parameters, which is the prerequisite for model creation.

II. Approaches to the Investigation of the Perceptual Space of Vibration

There are a multitude of studies that have investigated the perceptual space of vibrotactile perception. These studies can be divided into two main approaches to the problem, which depend on the experimental methods utilized to determine the perceptual dimensions [5]. These approaches can be described as the "psychophysical approach" and the "ecological approach."

A. The Psychophysical Approach

The psychophysical approach attempts to identify the properties of tactile perception. These properties include the perceptual threshold and the just-noticeable difference thresholds for level, frequency or perceived intensity [6]. The goal is to identify vibration patterns, tactile icons, or tactons [7] suitable for encoding new information for tactile feedback and to reveal dimensions that facilitate the discriminability of vibration. The dimensions of the perceptual space of vibration are interpreted as being implicit. Therefore, stimuli are often rated for their similarity without the necessity of utilizing rating criteria, e.g., specific perceptual attributes. A successive multidimensional scaling (MDS) reveals the underlying dimensions of the similarity ratings [5]. In a final step, an attempt is made to map explicitly interpretable labels onto these implicit dimensions.

[8] and [9] investigated sinusoidal and amplitude-modulated sinusoidal stimuli according to this procedure. They presented stimuli with a frequency range of 40 to 250 Hz and a level range of 30 to 40 dB above the sensation threshold as hand-arm vibration with a modulation frequency of 0 to 80 Hz. The participants rated the perceived dissimilarity among stimuli. MDS revealed two underlying perceptual dimensions: one dimension for low-frequency sensations and one dimension for high-frequency sensations. They hypothesize that sinusoidals that are amplitude-modulated with frequencies from 2-160 Hz likely elicit similar percepts as pure sinusoidals with a similar frequency. [10] investigated tactile rhythmic patterns in the frequency range from 200 to 300 Hz presented over a piezo-mounted handheld touch screen. Again, participants rated the perceived similarity among stimuli, and an MDS was calculated based on the results. The MDS revealed two underlying perceptual dimensions: even-uneven and low amplitude-high amplitude. Frequency was not found to be an additional dimension due to the small frequency range. [11] suggests that the dimensions uncovered by the MDS are independent from the specific device utilized for amplitude-modulated sinusoidal, rectangular and saw tooth finger vibration presented with different actuators.

The advantage inherent to the approach is that no criterion, i.e., attribute, is required for the rating of the stimuli [5], facilitating the task. Furthermore, it helps to limit the infinite design space to a finite set of discriminable options. A problem of this approach is that all stimuli need to be compared with each other, limiting the feasibility of utilizing many stimuli and thus potentially limiting the dimensions revealed by MDS [5]. Furthermore, it is often difficult to interpret the dimensions revealed by MDS [5], [12].

Based on similar studies in the auditory domain, it has been suggested by [7] that a relative comparison between two stimuli leads to a potential overestimation of differentiability. However, the MDS technique utilized in this approach is suitable to derive differentiability but unsuitable to derive intuitively conveyed perceptual properties [13], i.e., subjective sensations verbalizable by laypersons [14]. This approach facilitates the interpretation of the perceived relative difference between two stimuli by experts but does not enable the prediction of absolute perceptual attribute ratings of laypersons elicited by specific vibration.

The data acquired by this approach can be utilized to freely encode new information with the discriminable tactile stimuli to create tactile feedback, e.g., for hearing aids [15]. Another application is tactile codecs similar to mp3, which can eliminate indiscriminable stimulus variation, thus reducing the required bandwidth for the transmission of vibration [14].

B. The Ecological Approach

For the auditory domain, Gaver has suggested that psychoacoustic properties do not capture every aspect of auditory perception [16]. In everyday life, people perceive sound as a carrier of information about the environment. For example, an engine of an approaching car will emit a sound with specific temporal and spectral properties that elicit specific perceptual attributes, e.g., "humming," conveying information about the sound source. This example suggests an intrinsic relationship between sounds and intuitively elicited sensory-perceptual attributes learned from our experiences in everyday life. Based on this relationship, it is possible to synthesize sounds with certain sensory-perceptual properties and/or analyze sounds for their elicited properties [17]. He refers to this as the ecological approach to auditory perception. In agreement with these findings [14], [16], [17], it can be concluded that psychophysical properties do not capture every aspect of vibrotactile perception. We are frequently exposed to vibration in our everyday lives, e.g., when driving a vehicle. In such situations, vibration with specific temporal and spectral properties will elicit specific sensory-perceptual attributes, e.g., "bumpy." This suggests that it is possible to also approach tactile perception from an ecological perspective.

Few studies have been conducted with a focus on an ecological haptic perception approach. They have attempted to identify these perceptual properties by extracting them from a dictionary or by conducting free interviews with participants while presenting vibration. After this step, the identified attributes can be rated in an absolute rather than a relative manner for their suitability in describing different vibrations. A successive principal component analysis can help to identify redundant attributes [5]. It has been recently suggested by [2] that language is a promising way of quantifying user expectations for the translation into physical vibration parameters. However, no vibrotactile design language has yet been agreed upon.

One approach is to create a database of specific events and their elicited associations [18], [19]. However, this approach potentially produces different associations for different situations. In [20], two stimuli (16 Hz and 250 Hz) were presented with an ultrasound transducer array using acoustic radiation pressures to participants, and detailed descriptions of the tactile experiences were captured. Attempting to create sensory attributes suitable for many situations, they summarized the experiences into 14 categories that were dependent on the stimulus frequency (16-Hz Stimulus/250-Hz Stimulus): "puffs" / "breeze," "pulsing" / "flowing," "soft" / "dense," "coming & going" / "constant," "pointed" / "dispersed," "weak" / "strong," and "prickly" / "tingling." [21] assembled a database of 120 vibrotactile effects (VibViz). However, these vibrations were not completely generated by varying physical vibration parameters in a controlled way but rather assembled in a semi-systematic fashion and were thus only characterized by energy and duration. The effects were presented at the wrist with a C2 tactor actuator with a limited high-frequency range of approximately 200 Hz to 300 Hz without compensating the transfer function of the actuator. They selected a subset of sensory tactile perceptual attributes from the expert-defined touch dictionary of [22]. Users profiled each vibrotactile effect with these attributes. The goal was to aid designers in the selection of feedback from their database with specific perceptual property profiles. Extending their previous study [3], Seifi et al. attempted to identify the perceptual dimensions of the vibrations in their database and their perceptual attributes. They found four dimensions for sensory-perceptual attributes: complexity (e.g., "regular"), continuity (e.g., "continuous"), roughness (e.g., "smooth"), and duration (e.g., "long"). For such mapping databases, the design space is inherently limited to the vibration contained in the database. New vibrations can only be added by manually profiling them again because the observed discrete mappings to sensory attribute ratings cannot be generalized to other vibrations not contained in the database.

For the ultimate goal of predicting quality, affective ratings, e.g., pleasantness, are also important. [23] investigated the emotional ratings of amplitude-modulated sinusoidal vibration in the frequency range between 60 and 300 Hz with 5 different amplitude steps. Participants rated the elicited emotions in a valence arousal space. Surprisingly, despite their vibration frequency and level parameters spanning a major part of the tactile perceivable range, the emotion ratings varied across the entire arousal range but were focused only over a quarter of the valence scale, i.e., not being perceived as very positive or very negative. [24] investigated the relationship between physical vibration parameters and emotional attributes. They used 10 basic rhythmic vibration patterns selected from their database and introduced changes such as modifying tempo or energy. Participants rated the emotional attributes of agitation, liveliness and strangeness of these modifications. The results suggest a linear relationship between actuator output energy and agitation and liveliness. However, depending on the basic vibration, a different relationship can be observed. These findings suggest that a simple mapping between physical vibration parameters and affective perceptual attributes is difficult to obtain. One possible explanation might be found in the context-dependency of preference, i.e., quality judgments. Sound quality is known to be influenced by situational context [25]. If one compares the sound of waves crashing on the beach to the perceptually similar sound of the tire noise of passing cars, it is obvious that the former sound would likely be perceived as much more pleasant than the latter despite their temporal and spectral similarity. Thus, emotional ratings of tactile stimuli will likely be dependent on the context of their application and will likely not be universally mappable to physical vibration parameters. [24], [26] propose a multi-layer structure with engineering parameters mapped onto sensory attributes, which map onto affective attributes. This suggests that sensory-perceptual attributes might be more suitable for creating context-independent models. These models as well as application context specific expectations might facilitate the assessment of affective attributes.

The advantage of the ecological approach is that it enables communication with laypersons about explicit vibrotactile properties without the necessity of mapping implicit dimensions onto explicit perceptual properties [5]. Absolute judgments of sensory-perceptual attributes are potentially suitable for creating continuous mappings if vibration properties are systematically varied. Vibration created with such mappings could intuitively convey intrinsically encoded information without prior learning because laypersons can readily associate specific sensory-perceptual properties with specific vibrations due to their everyday-life experiences. However, it is difficult to identify relevant suitable sensory-perceptual attributes in the vast amount of verbal descriptions utilized to label vibration without missing potential dimensions [5], potentially resulting in many trials to rate each label for each vibration. Identification of all common sensory-perceptual attributes and a continuous mapping of their relationship to physical vibration parameters would enable the creation of models to design vibrations with specific sensory-perceptual properties, e.g., for tactile authoring [14], tactile product design or tactile feedback design. For the latter, such models could facilitate finding appropriate sensations for the intended feedback meaning of a tactile icon because the perceptual dimensions by which stimuli would be naturally sorted by user and their prior, intuitive associations are considered [27]. Furthermore, models could enable the automatic analysis of perceptual properties elicited by specific vibrations in product development.

C. *Requirements of a Tactile Design Language*

What are the requirements of a vibrotactile design language suitable for the creation of models?

1) Facilitate Explicit Communication with Laypersons: The terms should be intuitively understandable by potential future product users, i.e., laypersons, which would enable efficient communication without prior explanation, facilitating the assessment of actually desired, instead of supposedly desired, tactile properties. It has been suggested that the language utilized by laypersons differs from that of experts when describing product sounds, such as those from vehicles [28]. Therefore, the terms should be a relatively common part of everyday language. However, the ecological approach implies that only vibrations frequently encountered in everyday life are likely to reliably elicit perceptual attributes familiar to laypersons. Therefore, stimuli utilized for investigating elicited perceptual properties need to be sufficiently similar to frequently encountered vibrations.

2) Applicable Across Different Contexts: Furthermore, the elements of the tactile language should be mostly context-independent, i.e., suitable for an effective profiling of a wide range of vibrations. On the one hand, if the perceptual attributes are too general (e.g., "vibration"), their applicable domain would be so wide that they would not constrain vibration parameters. On the other hand, if the perceptual attributes are very specific associations ("cobblestone road"), their applicable domain would be too narrow to offer insights regarding different situations.

3) Sensory-perceptual Attributes: As argued in section II.B, affective attributes are likely to be influenced by context and personal preference. Therefore, they are not well suited for creating models applicable across different contexts. However, models of sensory-perceptual attributes can be one building block for potential models of emotional attributes among other blocks as context or preference-dependent factors.

4) Compact Set to Enable Effective Communication: Furthermore, the tactile design language should be compact, i.e., it should only contain the necessary sensory attributes. The number of perceptual attributes that should be contained in the set depends on two factors. On the one hand, there need to be sufficient attributes to differentiate all prominent percepts. On the other hand, it is well known that natural language contains many synonyms and antonyms. Strongly correlating perceptual attributes should be avoided so that the effort of profiling vibrations and creating models for these attributes is minimized. Another implication of that fact is that there is not only one set but instead potentially multiple sets of signal-describing perceptual attributes sufficient for mapping the perceptual space of vibrations.

D. *Goal of This Study*

This publication will focus on the creation of a sensory-perceptual attribute-based vibrotactile design language. The present study was designed to follow the ecological approach to tactile perception according to section II.B. Therefore, instead of assessing similarity ratings of stimuli followed by multidimensional scaling to reveal implicit perceptual dimensions, we began with a free association task to find the sensory-perceptual attributes commonly used to describe vibration. The elicitation approach was adapted from methods applied to the auditory domain [28] and the tactile domain for the niche of 14 vehicles' idle-mode seat vibrations [29]. The goal was to fulfill all requirements for sensory-perceptual attributes described in section II.C. The approach consists of two steps: The identification of sensory-perceptual attributes followed by the mapping of vibration parameters onto ratings of each attribute.

1) Identification of Sensory-perceptual Attributes: The first step was to find a compact set of mostly context-independent sensory-perceptual attributes suitable for covering the most prominent percepts of the most common seat vibrations occurring in everyday life. Everyday-life seat vibrations were generalized according to their excitation process to facilitate systematic variation of physical vibration parameters over the perceivable frequency and level range of tactile receptors limited by ISO 2631 exposure limits. The free verbalization interview used by [28] was selected as the most suitable method for identifying the perceptual attributes elicited by these vibrations. The large number of stimuli renders other methods where stimuli need to be compared directly, e.g., the Repertory Grid Technique Method, impractical. Laypersons were chosen as participants to explicitly identify attributes familiar to them. They were presented vibration stimuli and asked to describe their tactile percepts, which resulted in a very large number of words. Associations that were too general or too specific were discarded according to section II.C, as well as affective terms. First, frequently mentioned attributes were aggregated with more frequent attributes if they had the same word stem or were antonyms or synonyms. After that, all attributes below a low occurrence threshold were discarded as unimportant for defining the most common sensory-perceptual attributes. This filtering enabled focusing on the most common attributes for the subsequent experiments.

2) Mapping of Vibration Parameters onto Attribute Ratings: The second step was to examine the relationship between temporal and spectral vibration parameters and the sensory-perceptual attribute ratings. Therefore, for each stimulus, each suitable attribute was rated in a semantic differential test, which created a mapping between vibration parameters and the selected sensory-perceptual attributes. The perceived suitability for describing the stimuli was used to conduct a principal component analysis to sort out correlating attributes, thus further reducing redundancy. The result is a continuous mapping between the physical parameters of seat vibration and the ratings of a compact set of the most important sensory-perceptual attributes suitable for model building.

III. Identification of Vibrotactile Sensory-perceptual Attributes

A. Stimuli

In a previous study [30], we investigated the sensory-perceptual attributes of periodic vibration. However, periodic vibration represents only a fraction of seat vibration encountered in everyday life. Therefore, we chose to extend our previous study to nonperiodic vibration to find all sensory-perceptual attributes commonly used to describe frequently encountered vibrations. To elicit a sufficient number of perceptual attributes, the majority of everyday seat vibration should, in theory, be included in the elicitation task. Such vibration is encountered in many everyday-life situations, e.g., in cars, trains, ships or aircraft. Obviously, examining every possible scene would turn out to be difficult, if not outright impossible because of the effort required to record an infinite number of variations and present them to participants in an elicitation task. However, coming up with verbal descriptions of stimuli can be interpreted as a categorization task. The properties of the perceptual process of categorization enable a decomposition of the infinite number of variations into a finite set, as argued by Rosch [31]: "The world consists of a virtually infinite number of discriminably different stimuli. One of the most basic functions of all organisms is the cutting up of the environment into classifications by which nonidentical stimuli can be treated as equivalent." Thus, it is not necessary to consider an infinite number of stimuli but instead at least one stimulus for each attribute to be elicited in the perceptual space of everyday seat vibration. Furthermore, it implies that such a stimulus can deviate from a stimulus encountered to some extent while still being associated with the same perceptual attribute. If seat vibration recordings from real vehicle scenes are examined, their temporal and spectral structure can be generalized into four fundamental vibration patterns:

1) sinusoidal acceleration signals produced by periodic mechanical processes
2) amplitude-modulated (AM) signals, e.g., in the case of correlated periodic excitation
3) broadband signals caused by a superimposition of uncorrelated sources
4) impulse-like signals caused by impacts

Due to the limited frequency selectivity of tactile receptors (the just noticeable difference in frequency (JNDF) is approximately 30 % [32], [33]) and masking effects [34], [35], temporally and spectrally, more complex vibrations are likely difficult to resolve. As long as a generalized stimulus is perceived to be sufficiently similar to the real stimulus, the same perceptual attribute should be elicited, though possibly with a lesser perceived match. Thus, to avoid redundancy and to systematically represent the variation in everyday vibration, parameters of these basic signal patterns were varied.

The presented stimuli should span over the range in which tactile receptors are sensitive to vibration. Thus, the range of the signal parameters can be determined from the psychophysical literature. The perceivable range of seat vibrations covers frequencies from a fraction of one Hz up to approximately 500 Hz, with the perceptual threshold rising from approximately 80 dB(μm/s^2) to 120 dB(μm/s^2) [36]. The exposure limits for one-hour exposure as stated in [37] can be interpreted as a reasonable upper boundary for every-day vibrations. Other psycho-vibratory research findings, such as the just noticeable difference in level (JNDL) [38] and frequency (JNDF) [32], [33], were taken into account to create clearly distinguishable stimuli. In the area limited by the aforementioned boundaries, sinusoidal stimuli were distributed evenly. The frequencies of the stimuli were selected in such a manner that they extended the stimuli used in the study in [30]. For each of the 4 stimulus types, parameters were systematically varied.

1) Sinusoidal Stimuli: Stimulus frequencies were selected in a range from 1 to 500 Hz. Two vibration levels were chosen near the perceptual threshold and near the exposure limit. Weak vibrations had a level of 10 dB above the perceptual threshold (sensation level, SL). Strong vibrations had a level of 36 dB (SL), which was just below the one-hour exposure limit.

2) Amplitude-Modulated Stimuli: Amplitude modulation (AM) was introduced for a subset of the sinusoidal stimuli according to:

$$a\,(t) = A(1 + m\cos\left(2\pi f_m t\right))\cos\left(2\pi f_c t\right) \qquad (1)$$

where A is an acceleration constant, f_m is the modulation frequency, f_c is the carrier frequency, and m is the modulation index. The modulation frequency was chosen to always be a fraction of the carrier frequency. [9] used the sideband suppressed-carrier technique to generate stimuli. Generating AM stimuli with a variable modulation index instead facilitates potential future extensions of this study on partially modulated stimuli, i.e., stimuli with a modulation index of $m < 1$, reflecting the variance of everyday-life vibration, e.g., emitted by combustion engines. However, the modulation depth was defined to always have a value of $m = 1$ in this study to maximize perceptual dissimilarity compared to sinusoidal stimuli. The root mean square (RMS) levels were identical to the levels of sinusoidal stimuli with the corresponding frequency. Sinusoidal and amplitude-modulated sinusoidal stimuli were identical to those in [30].

3) Bandlimited White Gaussian Noise Stimuli: To facilitate comparison to sinusoidal stimuli, white Gaussian narrowband noise stimuli were created similarly. Apart from the center frequency f_c of the noise, the bandwidth f_b was also varied.

The center frequency was chosen depending on the bandwidth (25 Hz to 400 Hz). The bandwidth was halved in multiple steps from 400 Hz to 25 Hz to include a noise signal spanning the entire tactile receptor range, as well as narrowband noise sufficiently distinct from sinusoidal signals. The center frequency was selected depending on the bandwidth of the signal. The total RMS levels of the noise were adjusted to 10 dB and 36 dB above the perceptual threshold at their respective center frequencies. Due to limited data on the perceptual threshold for noise signals, the perceptual threshold for sinusoidal signals was used. However, studies concerning the perceived discomfort [39] indicate that the perceived intensity of sinusoidal vibration can be compared to the perceived intensity of band-limited noise with the same RMS level.

4) Impulse-like Stimuli: Impulse-shaped signals were based on signal patterns observable in a mass-spring-damper system excited by a shock. They can thus be interpreted as a sinusoidal stimulus with an additional decay [40]:

$$a\,(t) = \; Ae^{-\alpha t}\sin\left(2\pi f t\right) \quad \text{for } t > 0 \tag{2}$$

The resonance frequencies of the stimuli were selected to be comparable to sinusoidal stimuli. The exponential decay rates (α) were chosen to include the behavior of a highly damped ($\boldsymbol{\alpha} = 8$) and a weakly damped ($\boldsymbol{\alpha} = 2$) resonance system Because of the decaying characteristics of this signal class, the initial peak acceleration instead of the total signal RMS was chosen to characterize the vibration. The upper level was 42 dB (SL). Because of the fast decay and due to temporal energy integration properties of the tactile receptors [41], a threshold shift needed to be considered. Therefore, 30 dB (SL) was selected as the lower level of the stimuli to remain clearly perceivable. Successive impulses with a constant pause between them were also included in the experiment because such vibrations can occur on certain road types, e.g., motorways with concrete plates. The pause between impulses was defined as the period from the previous impulse falling below the perceptual threshold to the beginning of the successive impulse. An upper limit of a pause of one second was chosen in a preliminary experiment so that the resulting impulse sequence was still interpreted as one event rather than a succession of multiple single-impulse events.

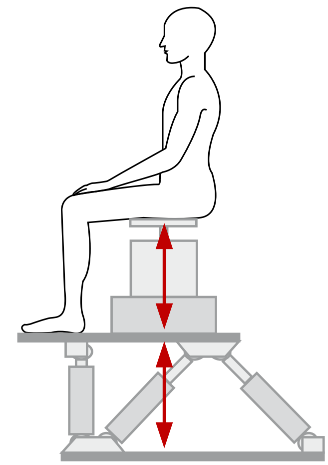

Fig. 1. Experimental setup for presenting vertical stimuli consisting of a hydraulic platform and an electrodynamic shaker. 10 dB (SL) stimuli were presented with the hydraulic platform up to 7 Hz, as well as 36 dB (SL) stimuli up to 15 Hz.

The duration of the stationary stimuli was 9 s with a fade-in and fade-out of 0.3 s. For impulse-like stimuli, a fade-in of half the oscillatory period of the impulse resonance frequency was utilized to enable correct reproduction. The sum of all stimuli for the experiment was 99. [5] argues that the stimulus set should be balanced to avoid missing characteristics of less dense data. The utilized stimulus set can be interpreted as sufficiently balanced due to the even distribution of the number of stimuli onto the 4 signal types (21 sine, 30 AM sine, 22 noise, and 26 impulse), as well as the even distribution of parameter variations.

B. Experimental Setup

The stimuli described in the previous section were presented in the Multimodal Measurement Laboratory [42] as vertical vibration for subjects seated in a Recaro racing seat. A hexapod platform reproduced low-frequency vibration, and an electrodynamic shaker reproduced high-frequency vibration. Due to the properties of the reproduction systems, the separation frequency between both systems depended on the level of the stimuli. The shaker was utilized above 7 Hz at 10 dB (SL) and above 15 Hz at 36 dB (SL). Both reproduction systems operated in their respective linear ranges. The setup is shown in Fig. 1. [43] emphasizes the importance of reproduction system calibration under the actual tactile experiment condition. Due to the different body characteristics, e.g., weight, the individual transfer functions differed as well. Therefore, the individual transfer functions were compensated with an FIR filter [44].

C. Experimental Design

To extend the perceptual attributes found in [29], [45], a free association task was conducted for all stimuli.

TABLE I
NUMBER OF OCCURRENCES FOR EACH SIGNAL TYPE AFTER EACH SUCCESSIVE REDUCTION STEP

Cumulative Filtering Step	Number of Occurrences (AM) Sine	Noise	Impulse
affective, connotative, nontactile removed	98	87	80
attributes with same word stem removed	93	80	72
less frequent synonyms and antonyms merged	39	35	42
infrequent attributes discarded	17	14	19

Participants were instructed to name all attributes that characterize the presented vibration. Because the participants were seated on the experimental setup, the experiment conductor manually entered the mentioned attributes separately for each subject and each stimulus. In addition to coming up with words themselves, participants were also handed a list with the perceptual attributes found in [29], [45]. All stimuli were presented in random order. Participants were instructed to come up with attributes describing the presented vibration but not with associations of specific situations (e.g., "cobblestone road") or with a general indication that a vibration or oscillation (e.g., "vibrating") was present. The time to think about associations for a stimulus varied by participant and was not limited to but typically did not exceed approximately one minute. Participants could repeat the stimulus as often as necessary. The experiment was conducted in two sessions of approximately one hour each to maintain participants' attention.

D. Participants

For the (AM) sine stimuli, 19 participants (12 male, 7 female) with an average age of 35 years (23 to 71 years) took part in the experiment. For the noise stimuli, 18 participants (12 male, 6 female) with an average age of 35 years (23 to 71 years) took part. For the impulse-like stimuli, 18 participants (12 male, 6 female) with an average age of 35 years (23 to 71 years) took part in the free association task. The study was conducted with the understanding and written consent of each participant.

E. Results

1) Description: Before analyzing the results, associations that were not within the focus of the study, i.e., if they clearly related to another modality, were too general or too specific, or were affective or connotative (see section II.C), were discarded. Due to similar associations for sinusoidal and AM sinusoidal stimuli, these two signal types were grouped in an (AM) sinusoidal group for the subsequent analysis. In whole, this experiment resulted in 98 unique attributes for (AM) sinusoidal signals, 87 unique attributes for noise signals and 80 unique attributes for impulse signals. Many associations were found for more than one signal type. It is obvious that attempting to find a mapping for each of the found attributes would not be feasible due to the many ratings required. However, it is known that natural language contains many synonyms and antonyms. Furthermore, it is likely that more frequently elicited attributes are more relevant for communicating about tactile perception because they will be understandable by most laypersons.

2) Aggregation and Prioritization: A series of aggregation and prioritization steps was conducted. The total number of attributes for each signal type after each successive reduction step is shown in TABLE I. To find the most common attributes, it would have theoretically been possible to directly filter the attributes by their number of occurrences. However, similar impressions described with differing attributes would have had a reduced ranking and would have thus been filtered out and been missing in the set of attributes. Therefore, aggregation of words with the same word stem and synonyms was conducted beforehand with the help of a machine-generated thesaurus [46]. Because there were clear antonym pairs only for some of the attributes, antonyms were also aggregated instead of creating attribute pairs that might be used in bipolar scales for the rating of the suitability in describing specific vibrations in section IV. Attributes occurring with low frequency were aggregated with more frequent attributes, adding their numbers of occurrences. This step also reduced the redundancy. However, a further redundancy reduction for attributes with a high number of occurrences was left for the principal component analysis in the successive step (see section IV) because it was expected to be more sensitive to subtler differences of the most common attributes. Because the goal of this study was to find the most common perceptual attributes, the aggregated attributes were filtered in two steps by number of occurrences. To discard attributes that only a few participants elicited across multiple stimuli, a relevance threshold of 15 % of the total occurrences for at least one stimulus was defined for each attribute. After this step, a global occurrence filter was applied to filter out attributes that were mentioned in less than 2 % of the judgments (number of participants times the number of stimuli) for each signal type.

These steps resulted in 21 attributes, which are shown in TABLE II. The German attributes were translated by a bilingual language expert. The translations were verified by presenting stimuli with high and low suitability ratings (see section IV) of each perceptual attribute to the expert.

IV. MAPPING THE RELATIONSHIP BETWEEN PHYSICAL VIBRATION PARAMETERS AND VIBROTACTILE SENSORY-PERCEPTUAL ATTRIBUTES

To create a compact perceptual attribute set, all attributes were checked for redundancy. Thus, the specific suitability of each attribute to describe each stimulus needed to be rated to conduct a principal component analysis.

A. Experimental Design

The perceptual attributes were split into groups of three attribute triples. All 99 stimuli described in section III.A were presented for each triple. For the rating of the specific

TABLE II
NUMBER OF OCCURRENCES OF EACH OF THE MOST FREQUENTLY ELICITED ATTRIBUTES FOR THE THREE SIGNAL TYPES AND THEIR TRANSLATIONS

Attribute		Number of Occurrences		
Translation	German	(AM) Sine	Noise	Impulse
weak	schwach	178	102	100
trembling	wackelnd	143	49	176
jolting	schlagend	136	32	243
bumpy	holprig	124	70	85
buzzing	summend	113	14	102
pulsating	pulsierend	108	(4)	104
tingling	kribbelnd	108	48	103
calm	ruhig	101	10	41
humming	brummend	99	17	54
rattling	ratternd	92	18	18
grinding	rauschend	78	22	(0)
shaky	rüttelnd	70	27	161
shuddering	Zittrig	54	19	26
throbbing	wummernd	47	(6)	77
up and down	auf und ab	32	11	72
uniform	gleichmäßig	30	33	(0)
decaying	abklingend	(0)	(0)	40
fading	nachschwingend	(0)	(0)	35
soft	weich	17	(16)	30
ticking	tickend	(17)	(1)	17
repetitive	wiederholend	(5)	(3)	14

Attribute occurrences below the per-stimulus occurrence threshold and below the global occurrence threshold of a signal type are in brackets

TABLE III
PRINCIPAL COMPONENT ANALYSIS (VARIMAX ROTATED) AND (SUB-) GROUPS WITH SIMILAR RATING PATTERNS

Attribute		Component				(Sub)
Translation	German	1	2	3	4	Grp.
bumpy	holprig	**.94**	-.26	.10	.09	1b)
buzzing	summend	-.19	**.94**	.13	.00	2
calm	ruhig	**-.76**	-.40	-.23	-.31	1a)
decaying	abklingend	.06	-.05	.01	**.96**	4a)
fading	nachschw.	.29	-.12	.06	**.91**	4a)
grinding	rauschend	-.01	**.84**	-.16	-.38	2
humming	brummend	.24	**.90**	.16	-.10	2
jolting	schlagend	.58	.05	.47	**.60**	4a)
pulsating	pulsierend	.47	.17	**.84**	.10	3
rattling	ratternd	**.82**	.42	.21	-.20	1b)
repetitive	wiederholend	.18	-.05	**.89**	-.34	3
shaky	rüttelnd	**.95**	-.14	.10	.14	1b)
shuddering	zittrig	**.93**	.13	.16	-.04	1b)
smooth	weich	**-.70**	-.41	-.19	-.28	1a)
throbbing	wummernd	**.73**	.20	.53	.21	1b)
ticking	tickend	.14	.18	**.92**	.19	3
tingling	kribbelnd	.01	**.95**	.19	.08	2
trembling	wackelnd	**.90**	-.33	.03	.19	1b)
uniform	gleichmäßig	-.15	.16	.52	**-.67**	4b)
up and down	auf und ab	**.80**	-.38	.03	.22	1b)
weak	schwach	**-.82**	-.36	-.25	-.25	1a)

Attribute loadings above 0.6 or below -0.6 shown in bold.

suitability of the perceptual attributes in describing the presented stimulus, subjects indicated the intensity of their associations on a quasi-continuous Rohrmann scale [47] with the equidistant verbal anchors “not at all” (0), “slightly” (25), “moderately” (50), “very” (75) and “extremely” (100). Before the experiment, there was a short training phase in which all participants were first presented different stimuli from across the full stimulus range. The time to rate an attribute triple for a stimulus was not limited but typically took approximately 10 seconds. Participants could repeat the stimulus but rarely did so. Due to the large number of trials, the ratings were conducted in four separate sessions of one hour each to keep participants’ attention.

B. *Participants*

A total of 29 native German speakers (20 male, 9 female) with an average age of 35 years (16 to 74 years) took part in each session. The study was conducted with the understanding and written consent of each participant.

C. *Results*

The experiment resulted in 21 attribute ratings for each of the 99 stimuli. The first step was to control each attribute for its general adequacy in reflecting any variation in physical parameters by corresponding rating differences. Thus, a repeated-measures ANOVA was conducted for each attribute over the 99 stimuli. The ANOVA results revealed the existence of highly significant effects ($p < 0.001$) for each attribute. Thus, all 21 attributes can be utilized to describe differences among stimuli.

To reduce redundancy, correlated attributes were identified. A matrix of mean ratings for each attribute for each stimulus formed the basis for a principal component analysis, which was conducted in SPSS. Four principal components explain 91 % of the observed variance. TABLE III shows the attribute loadings onto each component. For all components, different relationships between the physical stimulus parameters and ratings of attributes that loaded highly onto them could be observed. These relationships are discussed from a descriptive standpoint for each component.

1) Level and Low-Frequency Descriptive Attributes: Two subgroups of attributes were loaded on the first component. One subgroup had high positive loadings, while the other subgroup had high negative loadings.

a) Level Descriptive Attributes: The perceptual attributes “weak,” “calm” and “soft” belong to the first subgroup with highly negative loadings. Fig. 2 shows the mean suitability ratings and the 95 % confidence intervals (CI) for one of these attributes for sinusoidal signals. For 10 dB (SL), the suitability rating is high, and for 36 dB (SL), the suitability rating is 50 to 60 scale points lower. The influence of stimulus frequency on the suitability rating is small compared to the influence of stimulus level, with only an approximately 20-point increase in ratings towards higher frequencies. Therefore, these attributes were dominantly used to describe the level of sinusoidal vibration.

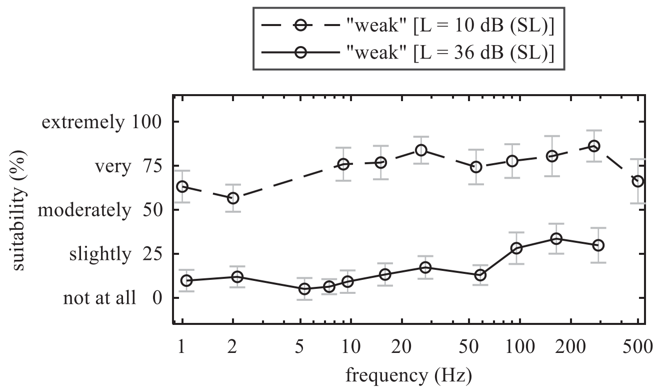

Fig. 2. Mean values and 95 % CIs of the attribute “weak” for sinusoids.

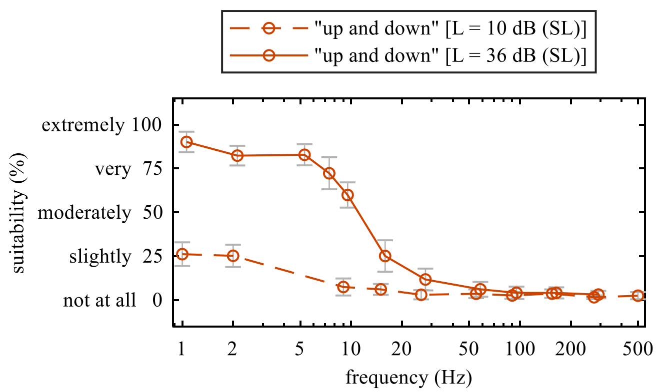

Fig. 3. Mean values and 95 % CIs of the attribute “up and down” for sinusoids.

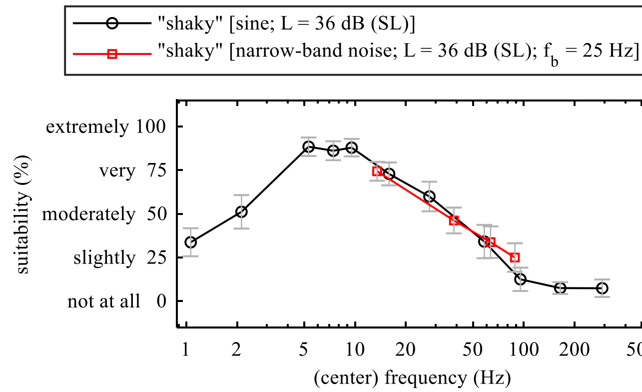

Fig. 4. Mean values and 95 % CIs of the attribute “shaky” for sinusoidal vibration compared to bandlimited white Gaussian noise vibration (represented at the center frequency) with varying center frequency.

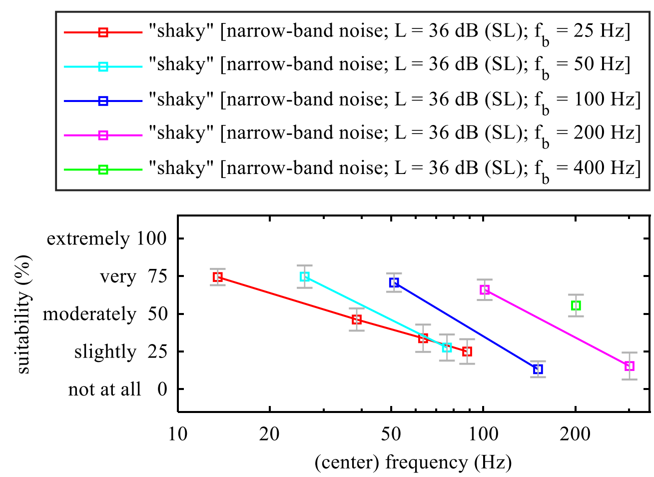

Fig. 5. Mean values and 95 % CIs of the attribute “shaky” for white Gaussian noise vibration at the center frequency with varying bandwidth.

Introducing modulation does not change the suitability rating of “weak.” The suitability rating also seems to be independent from whether a sinusoidal signal or narrowband vibration with the same RMS is presented. Because the perceptual threshold is not constant over the especially higher bandwidth noise signals, some minor differences can be attributed to the level of the noise signals being selected relative to the perceptual threshold at the center frequency. The suitability rating for decaying impulse signals for 42 dB (SL) is comparable to the 36-dB (SL) suitability ratings for sinusoidal signals. The reason for that difference lies in the decaying level of the impulse vibration compared to the constant level of the sinusoidal vibration. Therefore, these attributes were dominantly used to describe the level of vibration across all signal classes (correlation between the sensation level and “weak,” Spearman’s $\rho = -0.739$, $p<0.01$).

b) Low-Frequency Descriptive Attributes: Another subgroup of perceptual attributes had highly positive loadings on the first component and was used to describe low-frequency vibration. Attributes in this group are: “up and down,” “bumpy,” “rattling,” “shaky,” “trembling” and “shuddering.” Fig. 3 shows the suitability ratings for the attribute “up and down.” It represents the typical rating patterns observed in this group. The maximum suitability of approximately 90 rating scale points is at a frequency value below 35 Hz depending on the attribute. This pattern is more prominent for 36 dB (SL) (solid line). For the lower level of 10 dB (SL) (dashed line), the attribute is rated as not to slightly suitable (10 to 25 points) for describing the presented vibration, mostly independent from vibration frequency. Therefore, these attributes are not only frequency-dependent but also level-dependent. The introduction of modulation has a minor effect on the suitability ratings of these attributes compared to the effect of carrier frequency. Compared to sinusoidal vibrations, impulse-type vibrations elicit lower suitability ratings for these attributes. The reason for that difference again lies in the decaying level of the impulse vibration compared to the constant level of the sinusoidal vibration. In agreement with the findings for sinusoidal signals, a reduction in level leads to a reduction in suitability rating for the attributes in this subgroup.

The suitability ratings vs. center frequency for noise signals with a small bandwidth are also quite similar compared to sinusoidal signals. One example can be seen in Fig. 4. If the noise signal lies within the frequency range of a high attribute suitability rating for sinusoidal signals, it also has a high suitability rating. This trend remains when the bandwidth is increased (Fig. 5). However, with increasing bandwidth and center frequency, the suitability rating decreases. Because the

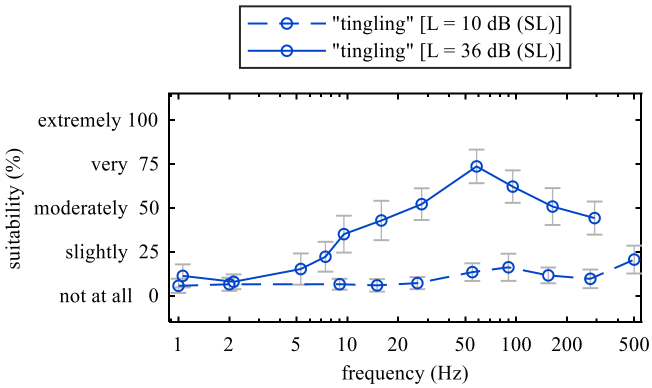

Fig. 6. Mean values and 95 % CIs of the attribute "tingling" for sinusoidal signals.

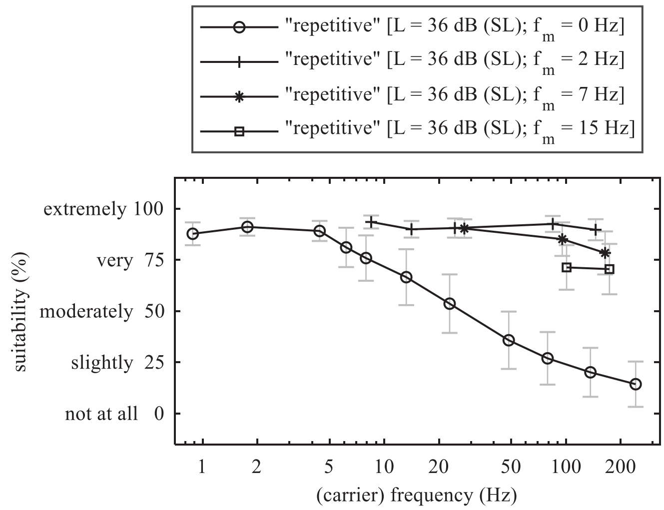

Fig. 7. Mean values and 95 % CIs of the attribute "repetitive" for AM-sinusoidal vibration with varying modulation frequency.

total RMS level was kept constant, the total signal energy is distributed over the increasing bandwidth. On the one hand, an increasingly large part of the signal energy gets shifted into a frequency range in which a sinusoidal signal with the same RMS level would only be rated as having low suitability for the respective attribute. On the other hand, this leads to a lower level for the part of the total energy in the frequency of maximum suitability for the respective attribute. The results suggest that the suitability of the perceptual attributes in this group depends on the total energy in the frequency range of its maximum suitability.

In summary, these attributes are used to describe high-amplitude, low-frequency vibration (correlation between (carrier, center, and resonance) frequency and "up and down," Spearman's $\rho = -0.732$, $p<0.01$).

2) High-Frequency Descriptive Attributes: The perceptual attributes having highly positive loadings on the second component were used to describe high-frequency vibration. Attributes in this group are: "tingling," "humming," "buzzing" and "grinding." These attributes show similar behavior as the attributes in the second subgroup loading on the first component. Fig. 6 shows the suitability ratings for the attribute "tingling." It represents the typical rating patterns observed in this group. However, the difference lies in their suitability maximum being at varying frequencies above 35 Hz depending on the attribute. The similarity to attributes in the second subgroup loading onto the first component can also be observed for the other signal types. The introduction of modulation has a minor effect on the suitability ratings of these attributes compared to the carrier frequency. In summary, these attributes are used to describe high vibration frequency and also vibration level (correlation between (carrier, center, and resonance) frequency and "tingling," Spearman's $\rho = 0.568$, $p<0.01$).

3) Attributes Used to Describe Modulation: The attributes "pulsating," "ticking," "repetitive" and "throbbing" load highly onto the third component. The main influence of the ratings of these attributes is modulation frequency with unmodulated, i.e., sinusoidal, vibration exhibiting up to 50 suitability rating points less compared to AM sinusoidal vibration. The effect is shown for one exemplary attribute, "repetitive," in Fig. 7. The effect is most prominent for high carrier frequencies and low nonzero modulation frequencies and is decreasing with rising modulation frequency, which can be observed for all attributes in this group. The comparison of noise to sinusoidal vibration showed no differences in suitability for these attributes. For single impulses, "repetitive" is not considered suitable for description. However, because the envelope of a vibration signal containing multiple impulses approximates the envelope of AM sinusoidal vibration, high suitability ratings can also be observed for these stimuli. Thus, these attributes are used to describe vibration with periodically rising and falling envelopes, i.e., modulation (correlation between modulation frequency and "repetitive, Spearman's $\rho = 0.583$, $p<0.01$).

4) Attributes Describing Temporal Irregularities: Two subgroups of attributes were loaded on the fourth component. One subgroup had high positive loadings, while the other subgroup had high negative loadings.

a) Attributes Used to Distinguish between Transient and Nontransient Vibration: The attributes "decaying," "fading" and "jolting" form the first subgroup and have highly negative loadings onto the fourth component. These attributes show 25- to 50-point-higher suitability ratings for impulses compared to sinusoidal vibration signals. The effect is most obvious for low nonzero decay rates and decreases with higher decays (Fig. 8). The comparison of single-impulse to multi-impulse vibration showed no differences in suitability for these attributes. No difference was also observed for noise signals that had similar suitability ratings as sinusoidal vibration. Only low-frequency modulated vibration had slightly higher suitability ratings compared to sinusoidal vibration. In summary, this attribute is used to distinguish between transient (single- and multi-impulse) and nontransient vibration signals (noise, (AM) sinusoidal) (correlation between decay rate and "fading," Spearman's $\rho = 0.715$, $p<0.01$).

b) Attributes Used to Distinguish between Periodic and Nonperiodic Vibration: The attribute uniform represents the

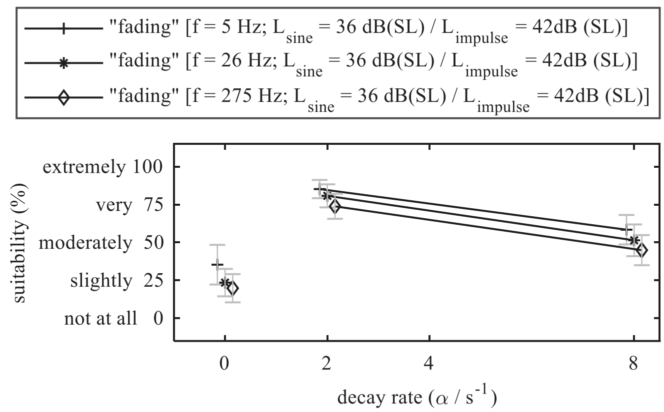

Fig. 8. Mean values and 95 % CIs of the attribute "fading" for decaying vibration with varying decay rate compared to sinusoidal vibration ($\alpha = 0$).

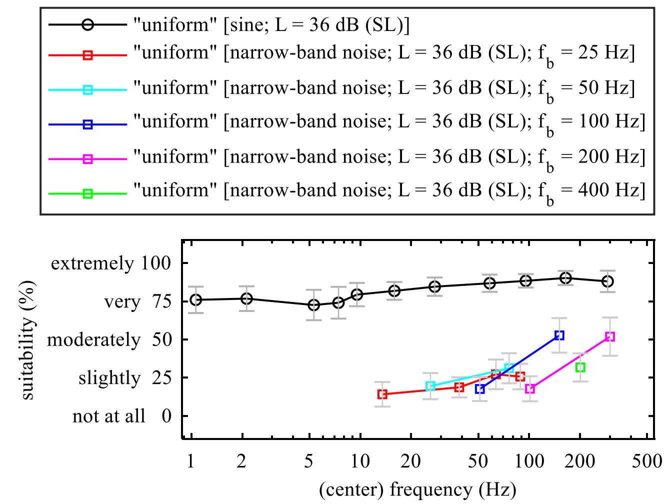

Fig. 9. Mean values and 95 % CIs of the attribute "uniform" for bandlimited white Gaussian noise vibration with varying center frequency and bandwidth compared to sinusoidal vibration.

second group loading highly onto this factor. The suitability ratings of "uniform" for sinusoidal and noise signals are shown in Fig. 9. The suitability ratings for sinusoidal signals (very suitable) are up to 60 points higher than the ratings of bandlimited noise signals (slightly suitable). In summary, this attribute was utilized to distinguish between stochastic and periodic vibration.

For single-impulse stimuli, suitability ratings were approximately 50 rating points lower compared to sinusoidal stimuli. However, periodically repeating impulses had similar suitability ratings as sinusoidal stimuli. In comparison to AM sinusoidal stimuli, sinusoidal stimuli elicited 20-points-higher suitability ratings (correlation between bandwidth parameter and "uniform," Spearman's $\rho = -0.355$, $p<0.01$).

D. Summary

The principal component analysis shows that there is much redundancy in the most frequent attributes. A minimal set of features should be selected to facilitate effective profiling and communication concerning the most salient sensory-perceptual properties. One sensory attribute out of each of the four groups might be sufficient to represent most of the variance observed in the perceptual space of seat vibration. However, it would be reasonable to also consider the subgroups of the first and fourth component. This is because the inverse loading onto the component does not imply a simple inversion of suitability rating patterns between the subgroups, i.e., there is no perfect anticorrelation among the attributes of the different subgroups (Pearson correlation $.45 < r < .83$). Two attributes with similar loadings onto the first factor can show different rating patterns in one stimulus subdomain, as evident when comparing "weak" (Fig. 2) to "up and down" (Fig. 3) for sinusoidal signals. Thus, to find a good compromise between explanatory power and compactness, it seems reasonable to select one attribute to represent each of the aforementioned six groups (e.g., "weak," "up and down," "tingling," "repetitive," "even" and "fading") instead of only 4 attributes or all 21 attributes. This selection would also limit the effort required for potential future modeling of the attributes.

V. Discussion

The goal of this study was to progress towards a more efficient tactile design strategy that derives optimal vibration parameters from tactile perceptual properties expected by potential users. The first experiment identified sensory tactile perceptual attributes that are elicited by everyday-life vibration. A large number of attributes are impractical for an efficient profiling of the perceptual properties of vibration. Therefore, a second experiment helped to identify six groups of redundant attributes, which are sufficient to represent the identified sensory tactile perceptual dimensions. By selecting one attribute from each group, a standardized sensory tactile design language can be defined. We suggest the attributes "weak," "up and down," "tingling," "repetitive," "even" and "fading." This design language is suitable for communication with potential users about elicited or expected tactile sensory-perceptual properties of sinusoidal, AM sinusoidal, bandlimited white Gaussian noise and impulse-like seat vibration. Thus, the design language can be used to create perceptual profiles, which provide the designer with a perceptual specification.

Furthermore, the relationships between the physical vibration parameters (level, frequency, modulation frequency, bandwidth and decay rate) and perceptual attribute ratings were characterized for each of the six attribute groups. The first attribute group can be represented by the perceptual attribute "weak," which is highly negatively correlated to the sensation level of the vibration. The second attribute group can be represented by the perceptual attribute "up and down," which is highly negatively correlated with vibration frequency. The third attribute group can be represented by the perceptual attribute "tingling," which is highly positively correlated with vibration frequency. The fourth attribute group can be represented by the perceptual attribute "repetitive," which can be used to describe AM vibration and is thus highly correlated with modulation frequency. The fifth attribute group can be represented by the perceptual attribute “fading,” which can be used to distinguish between transient and non-transient vibration signals and is thus highly correlated with the decay rate. The sixth attribute group can be represented by the perceptual attribute “uniform,” which can be used to distinguish between stochastic (noise) and periodic vibration and which is negatively correlated with the bandwidth parameter. In combination with the presented physical parameter vs. attribute rating curves, these results may help designers to derive optimal vibration parameters for a tactile perceptual specification expected by potential users for a feedback effect. Furthermore, the observed relationships are the basis for models, which might automate the defining of the physical vibration parameter from such perceptual specifications.

These findings extend the perceptual dimensions suggested by other studies. Amplitude was suggested to be represented by one perceptual dimension by [10] in agreement with the attribute group represented by “strong” – “weak.” The temporal structure was suggested by [10] to be reflected in the “even” – “uneven” dimension, likely in agreement with the attribute group represented by “uniform.” A dimension representing high-frequency stimuli and a dimension representing low-frequency stimuli were suggested by [43], found by [8], [9], and also confirmed in this study with a high-frequency attribute group (e.g., “tingling”) and a low-frequency attribute group (e.g., “up and down”). Furthermore, [9] hypothesized that sinusoidals that are amplitude-modulated with frequencies from 2-160 Hz likely elicit similar percepts as pure sinusoidals with a similar frequency. However, there seem to be two distinct dimensions for low-frequency vibration (e.g., described by “up and down”) and modulated vibration (e.g., described by “repetitive”), which was also suggested by [20].

These previous studies each utilized stimuli sets with limited vibration parameter variation, e.g., sinusoidal excitations only or frequency variation only. Because the stimulus set determines the observable perceptual dimensions, each study identified only a subset of these five perceptual dimensions. By utilizing a stimulus set that includes vibration parameter variation of the majority of excitation patterns encountered in everyday life, it became possible to verify that these perceptual dimensions can be found simultaneously, suggesting that they are indeed nonredundant. Previous studies presented vibration at the finger [10], [43], hand [8], [9] or wrist [21], while the current study presented vibration at the thighs. The emergence of these perceptual dimensions independently from the location of introduction suggests that they are universal for vibrotactile perception. By simultaneously including impulse-like stimuli, the existence of a sixth dimension related to transient changes represented by “fading” is suggested. The inclusion of more perceptually distinguishable dimensions can facilitate the creation of tactons that are more distinguishable [43].

Similarity judgment-based investigations of the sensory perceptual space [8–10], [43] identified perceptual dimensions related to physical vibration parameters. This method did not facilitate inference regarding the interpretation of these dimensions by laypersons, however, in contrast to the semantic differential method followed in this study. Furthermore, the similarity judgments between vibrations differing in their physical parameters only enable inferences regarding perceptual differences. The quantitative judgments of the perceptual attributes obtained in this study demonstrate a relationship between the physical parameters of seat vibration and attribute ratings. Interestingly, the attribute ratings seem to be comparable for different locations of introduction (hand vs. thighs), but the same vibration parameters [30].

Explicit communication with laypersons regarding sensory tactile perceptual properties relies on verbalizable familiar attributes, which seem to be inherently correlated, at least partially. Nonorthogonal attributes imply that theoretically contradictory attribute ratings could be defined by users. However, from a practical standpoint, laypersons should be intuitively aware of the inherent partial correlation among attributes, which would thus likely be reflected in such ratings. For example, they know that a vibration perceived as “slightly weak” (or as very intensive) is implicitly usually either “very up and down” or “very tingling” at the same time.

In [3], quantitative ratings of sensory-perceptual attributes were also obtained to generate an effects database containing high-frequency vibrations. In contrast to this study, the transfer function of the reproduction system was not compensated, which impeded the transfer of the observed mappings between vibrations and perceptual attributes to other reproduction systems.

Another difference between [3] and this study can be explained by the different stimuli selection strategies. The vibration effects utilized by [3] were not systematically varied according to their physical parameters, such as frequency. By generalizing everyday-life vibrations into excitation patterns, a systematic variation of their vibration parameters ((peak) level, (center/carrier) frequency, bandwidth, modulation frequency and exponential decay rate) became possible in this study. After surveying future users regarding the expected perceptual attribute ratings of a feedback effect, the design engineer wants to find vibrations that actually elicit these target perceptual attribute ratings. Databases with discrete mappings of vibration effects to attribute rating profiles, such as from [3], limit the selection to the existing effects and might require additional tuning [24] to produce vibrations eliciting target attribute ratings exactly. The presented relationships between physical vibration parameters and perceptual attribute ratings enable a much more flexible, continuous definition of the optimal vibration parameters, which ensures the elicitation of the target attribute ratings. The automation of this process would require the creation of models from the observed relationships.

While the suggested approach to tactile design might be feasible for vibration in general, the results of this study apply to the design of seat vibration in particular. Tactile feedback at the seat is frequently utilized in vehicles for a variety of applications because the driver’s visual and auditory channels are highly loaded. According to [48], there are four domains where tactile feedback is used: safety, assistance, fun, and efficiency. Safety can be enhanced by tactile warning feedback [49], e.g., guidance cues for lane departure warning, vehicle blind spot warning [50] or collision warning systems [51]. Feedback can be utilized in driving assistance, e.g., for the handover from autonomous driving, call notifications, or maneuver and navigation support. Fun might be increased by enhancing the perceived tactile sportiveness during acceleration by providing additional vibration [52].

Such applications typically aim to convey multiple tactile feedback messages to the user that communicate specific events or states of the system. The seat vibration feedback can be spatially encoded with multipoint excitation [51], [53]. The findings of this study might facilitate a temporal or spectral coding, as in [49]. Utilizing the proposed design method, the design engineer would provide semantic descriptions of the various feedbacks (e.g. a warning message) to potential users. He would survey them with the design language to obtain perceptual specifications of each message. Instead of relying on trial-and-error strategies, the designer could then translate these specifications into optimal seat vibration parameters using the observed physical parameter vs. attribute rating curves (possibly implemented into models). Since the expected and elicited perceptual properties (e.g., high uneven rating of the warning feedback) will match, the users would more likely intuitively interpret the message correctly and judge it favorably compared to a vibration arbitrarily assigned to the feedback message. Furthermore, the translation process might guide trade-offs between selecting simpler vibration actuators and deviating from the perceptual specifications.

In many product development scenarios, vibration is produced by, for example, actuators of limited capabilities, machines whose excitation cannot be varied arbitrarily by dampening, or resonance frequency shifts. An analysis model could predict the attribute ratings elicited by the constrained vibration. The degree of discrepancy between tactile sensory attribute ratings elicited by specific vibrations and the ratings expected (assessed from verbal descriptions) in a situational context might provide a meaningful predictor for tactile quality. Such a procedure might be more efficient than an iterative prototype-based approach with perceptual studies.

Eliciting the expected perceptual attributes could also be useful for authoring plausible vibrations for virtual reality applications, e.g., in entertainment parks or cinemas. The content designer could use the sensory tactile design language to obtain the sensory tactile perceptual attribute ratings expected by the user for a situational context, e.g., driving in a vehicle on a cobblestone road. A synthesis model could be constructed that generates seat vibrations from such a rating profile and elicits the desired perceptual attributes. If the elicited sensory-perceptual properties match the expected properties, the vibration should be perceived as plausible [54]. The feasibility of such an approach was demonstrated by [55]. They synthesized vibrations from expected ratings of the sensory tactile perceptual attributes of the design language suggested by this study. The synthesized vibration was perceived as plausible as recorded vibration in the context of the audio-visual scene presented in a virtual environment.

This work should be extended by utilizing the observed physical parameter vs. sensory attribute rating curves to build models for each attribute of the suggested sensory tactile design language. In the course of such an extension, it is likely necessary to obtain observations for more vibration signals. For example, interactions of multiple basic signals might be examined. Furthermore, it should be investigated whether the attributes of the suggested design language are also sufficient for describing vibrations introduced at other locations of excitation, e.g., hand-arm vibration or fingertip vibration. A comparison of seat vibration to hand-arm vibration suggests that identical vibrations elicit very similar sensory-perceptual attribute ratings at both locations of excitation [30].

Acknowledgments

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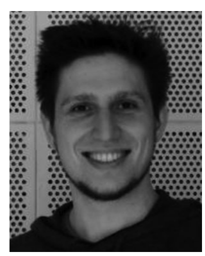

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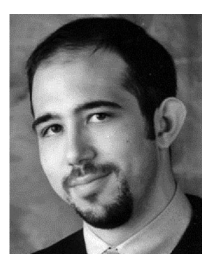

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