Tactile Design: Translating User Expectations into Vibration for Plausible Virtual Environments*

Robert Rosenkranz, M. Ercan Altinsoy

Abstract— **The aim of this paper is to demonstrate a novel design strategy for whole-body vibration based on user expectations which facilitates product design and the creation of plausible virtual environments. In both applications vibration parameters need to be derived from user expectations. Users can quantify their tactile expectations by rating a compact set of familiar sensory perceptual attributes (e.g. "tingling", "weak") without prior training. These ratings could be translated into parameters of vibration eliciting the expected perceptual attributes with the help of the relationship uncovered in a previous study. But are such attributes useful for the synthesis of whole-body vibration? To answer this question audio-visual-tactile vehicle scenes were recorded and rated for their elicited perceptual attributes. Subsequently scenes with vibration synthesized from these ratings were created. In a second experiment recorded scenes and synthesized scenes were rated for their perceived plausibility. Results show that plausibility ratings are extremely similar between recorded and synthesized vibration despite clear temporal spectral differences. These findings suggest that the plausibility illusion can be produced by presenting vibration which elicit the expected perceptual attributes. Thus, tactile perceptual attributes are sufficient to quantify user expectations from which plausible vibration can be systematically designed.**

I. Introduction

User expectations play a central role not only for product design but also for the creation of plausible virtual environments (VE). In both applications such expectations need to be quantified and vibration parameters derived from them.

In product design the user expectations are essential to the perception of quality. While using a product the user will compare his perception of the product with his expectations on the desired product properties [1]. When designing vibrotactile features e.g. for driving assistance systems it is necessary to create a tactile feedback eliciting the expected perceptual properties conveying information about the vehicles state. The quantification of expectations would greatly simplify guaranteeing product quality. Desired physical properties cannot be described by non-expert users i.e. laymen directly. Thus a design language would be required which can be understood by laymen but which is also suitable for engineers to derive physical properties.

In the context of virtual reality (VR) user expectations are essential for the plausibility illusion. VR aims to enable its user to react and interact with the presented situation as they would within a real situation. Slater [2] argues that there are two factors involved: the place illusion and the plausibility illusion. The place illusion is related to the concept of immersion and is influenced by the limitations of the reproduction systems of the VR (e.g. latency, display resolution). The plausibility illusion is related to the properties and the condition of the presented environment and is influenced by the user's perception i.e. his expectations on this environment. A systematic approach to elicit the plausibility illusion would facilitate the design of VEs.

Therefore, this study attempts to quantify tactile user expectations using tactile perceptual attribute ratings and to translate them into spectral temporal vibration parameters for whole-body vibration i.e. synthesize specific vibration. The implicit hypothesis of this approach is that verbalizable user ratings of tactile perceptual attributes are sufficient to capture the variability of vibration encountered in everyday life. There are two reasons why expectations in the context of the plausibility illusion are an easier domain to test this hypothesis, especially when choosing a familiar situation as driving in a vehicle. First, subjects will likely have very similar expectations on vibration because of shared experience e.g. with cars. Second, expectations are more likely to be uninfluenced by personal preferences, if they refer to vibration in specific situations in contrast of potentially desired vibration of a future product. Therefore, audio-visual-tactile vehicle scenes were recorded and rated for their elicited sensory perceptual attributes. Subsequently scenes with vibration synthesized from these ratings were created. In a second experiment recorded scenes and synthesized scenes were rated for their perceived plausibility. By comparing plausibility ratings between recorded and synthesized scenes it is possible to make inferences about whether the selected tactile perceptual attributes are sufficient to synthesize plausible vibration.

II. Determining a Tactile Design Language Suitable for Vibration Synthesis

A. Existing Approaches

The first step was to quantify tactile user expectations in a way which is suitable for vibration design. Gaver has described an interesting approach for the auditory domain [3], [4]. He argues that in everyday life sounds are a carrier of information. The physical properties of the sound producing event influence the spectral temporal properties of the sound and thus its audible source attributes. E.g. a motor is producing an amplitude modulated sound, which can be identified by its "humming" sound. The signal describing verbalizations of the sound can be the basis for the synthesis of sounds. The synthesis needs to be accurate enough, to produce relevant perceptual attributes. This approach might also be transferred to the tactile

*Research supported through DFG AL1473/5-1.

R. Rosenkranz and M. E. Altinsoy are with the Technische Universität Dresden, Chair of Acoustic and Haptic Engineering, 01062 Dresden, Germany (corresponding author to provide phone: +49 351 463 33547; fax: +49 351 463 33547; e-mail: robert.rosenkranz@tu-dresden.de).

domain: In everyday life humans are frequently exposed to vibration, e.g. when driving a vehicle. Depending on their temporal spectral properties certain information about the environment is conveyed, e.g. "tingling". Therefore, a vibrotactile design language needs to be identified, which is suitable for the quantification of perceptual vibration properties frequently encountered in everyday life.

There is no agreed vibrotactile design language yet [5]. [6] and [7] determined the perceptual dimensions of textures. Building onto [6] perceptual attributes of vibrotactile feedback have also been examined, especially for vibration applied to the fingertip or arm. [8] created a 120 item vibration library. They utilized a small bandwidth actuator with a limited frequency response in the range from 200 to 300 Hz. Thus, they focused on the variation of the temporal envelope with the goal of rather constructing tactile effects then representing naturally occurring vibration. They collected associations of test subjects for each vibration. In a follow-up study [9] they tried to determine relationship between vibration parameters of these 120 stimuli and the user perception. They identified 4 dimensions of sensory perceptual attributes for their stimulus space: complexity (e.g. regular), continuity (e.g. continuous), roughness (e.g. smooth), and duration (e.g. long). However, they did not identify a continuous mapping between physical vibration parameters and the sensations associated with them.

In another approach it was attempted to analyze the perceptual space of sinusoidal [10] and amplitude modulated stimuli [11] in order to identify dimensions which facilitate the discrimination of vibrotactile stimuli. They presented a frequency range of 40 to 250 Hz and level range of 30 to 40 dB above sensation threshold for hand-arm vibration. Subjects rated perceived dissimilarity between stimuli. Multidimensional scaling revealed two underlying dimensions: one dimension for low frequency and one dimension for high frequency.

B. *Requirements for a Tactile Design Language for vibration synthesis*

There are multiple requirements to a vibrotactile design language which could facilitate the synthesis of vibration:

First, it must be intuitively understandable for the future users (i.e. laymen) of the VE or the product, to enable explicit communication about expectations without prior training.

Second, its elements should have a direct relationship to physical vibration properties. In the auditory domain it is well known [12] that sound quality is dependent on the situational context. Thus sensory perceptual attributes are much better suited than affective attributes i.e. preference related attributes (e.g. "annoying") to derive vibration parameters independently from situational context.

Third, the elements of such a language should also not be specific associations ("cobblestone road") and not too general ("vibration") to enable the usage across situations while facilitating the translation into vibration parameters.

Fourth, since vibration can be understood as a carrier of information about the environment, their temporal spectral properties are closely linked to the elicited perceptual attributes. This implies that users can likely only come up with perceptual attributes reliably for the subset of vibration which is sufficiently similar to vibration encountered in everyday life. Therefore, the stimuli, on which a model is to be built, should be similar to vibration encountered in everyday life while at the same time allowing the creation of a continuous mapping between vibration parameters and the perceptual attributes elicited by them.

C. *Assessing the required design language*

In an attempt to fulfill these requirements, a study on the perceptual attributes of whole body vibration was conducted by the authors [13]. Whole-body vibration encountered in everyday life were generalized to typical physical excitations processes, i.e. periodic movements were generalized to amplitude modulated sinusoidal signals. This enabled the systematic variation of stimulus parameters: level (10 dB to 36 dB over sensation threshold), frequency (1 Hz to 500 Hz), modulation frequency (2 Hz to 16 Hz) thus facilitating the building a continuous mapping to perceptual attributes. All parameter ranges were selected to cover the perceivable frequency range of tactile receptors from a fraction of one Hz to about 500 Hz [14]. The exposure limits for one hour exposure [15] were selected as an upper boundary for every-day vibration. They determined the most frequently used sensory perceptual attributes in a free interview with laymen, which are suitable for describing periodic vibration across specific contexts. In a second step each common perceptual attribute was rated for its suitability in describing each presented vibration on a quasi-continuous rating scale with verbal anchors according to [16].

However, besides periodic movements there are broadband structural excitation and impact excitation is also commonly encountered. Therefore, noise and impulse like stimuli [17] were also presented in a free interview. For noise stimuli parameters of bandlimited white Gaussian noise (level, center frequency and bandwidth) were systematically varied. The same stimuli levels (10 dB and 36 dB above sensation threshold) were used as in [13]. The bandwidth was varied from 25 Hz to 400 Hz. The center frequency was varied depending on the bandwidth from 14 Hz to 300 Hz.

For impulse-like stimuli an exponentially decaying sinusoidal vibration was utilized to account for the temporal structure of the response of mass spring damper systems to impulse excitation as commonly encountered in situations with whole-body vibration i.e. in machines, e.g. cars. Because of the much shorter duration of the impulse-like stimuli higher vibration levels (30 dB and 42 dB above sensation threshold) were used. The resonance frequency was varied from 5 Hz to 90 Hz and the exponential decay constant of the resonance frequency was varied from 2 1/s to 8 1/s to cover the range of vibration occurring in everyday life.

The attributes most commonly mentioned in the free-interview stage of each stimulus domain were collected, according to method used for periodic vibration [13] resulting 21 unique attributes in total across all three domains. Subsequently the suitability of each attribute in describing each of the 107 stimuli was rated on a quasi-continuous scale with verbal anchors (0 equivalent to "not", 100 equivalent to "very"). This resulted in ratings in the range from 0 to 100 for each attribute for each stimulus.

When a factor analysis is conducted in SPSS on all attribute ratings for all stimuli, four factors emerge that explain over

90% of the observed variance, see *TABLE I*. A bilingual language expert translated the German attributes aided by the presentation of stimuli for which test subjects had rated the attribute as highly or weakly suitable in describing the stimulus.

TABLE I. PRINCIPAL COMPONENT ANALYSIS (VARIMAX ROTATED) TO IDENTIFY CORRELATING ATTRIBUTES AND TO SELECT A COMPACT SET OF ATTRIBUTES (BOLD)

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

The first factor contains two subgroups of attributes: attributes used for describing vibration level (e.g. weak") and attributes used for describing low frequency vibration (e.g. "up and down"). The attributes loading onto the second factor are used for describing high frequency vibration (e.g. "tingling"). Attributes used for describing modulation (e.g. "repetitive") load onto the third factor. The fourth factor contains two groups of attributes. In the first group attributes ("fading") are used to distinguish impulse-like vibration from stationary vibration. The attributes in the second group ("even") are used to distinguish periodic vibration from non-periodic vibration.

In order to allow an effective profiling of the perceptual properties of vibration a minimal number of explicit perceptual attributes should be utilized. Therefore, instead of constructing four implicit perceptual features from all 21 perceptual attributes ratings, a minimal number of attributes representing the four factors should be selected. The analysis suggests that ratings of one attribute for each of the six groups (e.g. "weak", "up and down", "tingling", "repetitive", "even", "fading") are likely sufficient to capture the perceived sensory properties of vibration instead of all 21 attributes.

III. QUANTIFYING TACTILE USER EXPECTATIONS

A. *Experimental Design*

The next step was to utilize the tactile language from section II for the quantification of tactile expectations on a set of scenes with real vibration. One of the most frequent contact with whole-body vibration is in cars. Therefore, a set of representative audio-visual-tactile scenes was recorded and subsequently presented to test subjects. For each multimodal scene, each of the selected six perceptual attributes was rated on a quasi-continuous scale with verbal anchors implemented as a MATLAB graphical user interface (GUI) in the same way as for the rating of generalized vibration in section II. All stimuli were presented in random order.

B. *Stimuli*

19 commonly encountered vehicle scenes of different driving conditions in an average middle-class vehicle (Renault Scenic 1.6) were chosen as being representative of whole-body vibration encountered in everyday life (see TABLE II). Twelve scenes were selected for their quasi stationary vibration. Seven scenes were included to cover impulse-like events, i.e. shocks. In order to be able to present identical stimuli to all test subjects, all audio-visual-tactile scenes were recorded. Vertical whole-body vibration was recorded with a seat pad accelerometer (B&K 4515B) and low frequency vibration with a Kistler 8305B10 sensor. Video recordings were conducted using a Canon EOS 600D with an optical image stabilizer lens. For audio recordings B&K 2671 ICP microphones were mounted on the head rest of the driver's seat to record the sound at driver's ear position.

C. *Experiment Setup*

All recorded scenes were presented in the Multimodal Measurement Laboratory [18] of the Chair of Acoustics and Haptics (see Figure 1). Low frequency vibration was presented vertically with a hexapod platform and high frequency vibration with an electrodynamic shaker as section II. In order to account for individual differences (e.g. weight) the transfer function for each test subject was compensated with an FIR filter [19] to ensure correct reproduction. To specifically assess tactile attributes elicited by the impulse-like events, a "Rate now" subtitle was displayed for the duration of the event. The recorded videos were presented with a projector. A wave field synthesis system with 464 Speakers was utilized to play back audio recordings as focused sound sources placed next to the ears of test subjects to recreate the car environment.

D. *Subjects*

A total of 35 German laymen (12 male, 23 female) with an average age of 26 years (20 to 61 years) took part in the experiment. The present study was conducted with the understanding and written consent of each participant. All stimuli of the

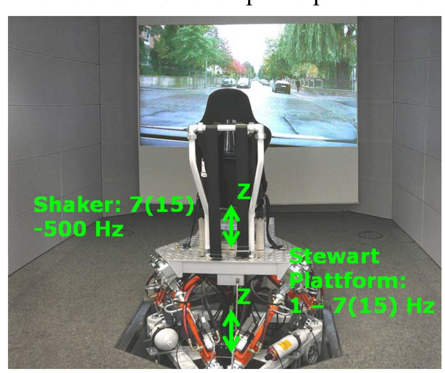


Figure 1. The tactile stimuli described in section II were presented on the depicted whole-body reproduction system (with frequency range for low sensation level (and high sensation level)) For the presentation of audio visual tactile scenes also audio and video were presented.

present study were below the 1 h exposure threshold defined in [15] which was the approximate experiment duration.

E. *Results*

The experiment resulted in a rating profile for each of the 19 scenes consisting of judgements for each of the six perceptual attributes (see TABLE II). This quantification of tactile expectations provided the necessary basis for the subsequent vibration synthesis.

IV. Translating User Expectations into Plausible Vibration

A. *The plausible approach to reproduction*

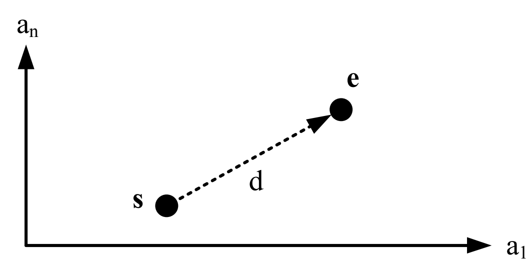
The focus in this study was to create the vibration expected in the context of virtual scenes. Therefore, the next step was to systematically evoke the plausibility illusion, which is closely related to user expectations [2] and which is besides the place illusion the main requirement for realistic action in and reaction to virtual reality. Thus, user expectations needed to be translated into vibration in a way which would evoke the plausibility illusion. There are two approaches to presenting stimuli for VE [20]: The authentic approach and the plausible approach. The authentic approach tries to evoke the same percepts in the VE as in the corresponding specific real environment, as required mostly for A/B comparisons. The goal of the plausible approach is to evoke percepts in the VE that could have occurred in a comparable real environment, known or unknown to the user. Therefore, in order to decide whether the presented vibration is plausible, the user compares the elicited perceptual properties to the relevant expected perceptual properties. This approach is sufficient for most virtual reality applications as e.g. training simulators or entertainment. The plausible approach has many advantages compared to the authentic approach. It doesn't necessarily require a prior recording of vibration, which enables the synthesis of vibration for scenes for which recording is impossible, e.g. for a car not build yet. If only the relevant perceptual attributes need to be elicited, the required properties of the reproduction system (e.g. bandwidth) are potentially lower. Expectations might even require vibration parameters for the VE which differ from vibration parameters encountered in the corresponding real environment. When conflicting cues are presented to different modalities the percept might be dominated by one modality, potentially leading to different expectations then for a unimodal presentation [21]. The viewers of a basketball game broadcast might perceive it as more plausible with their audio-visually influenced expectations on tactile feedback for dribbling fulfilled, despite such a feedback not necessarily being available in the venue itself. Expectations can also be formed by media exposure, e.g. spaceships emitting sound in vacuum. Relying on libraries with specific feedback for specific events as [22] is one possibility to create plausible haptic feedback. However, a model based plausible vibration synthesis directly from expectations appears to be more flexible and more effective.

B. *Plausibility as a Distance in a Feature Space*

In contrast to the place illusion, the plausibility illusion has received little attention [2]. [23] argues for auditory VEs that plausibility judgements can be interpreted as a distance measure between an expected perceptual object and the elicited perceptual object in an interindividually comparable n-dimensional space of relevant, perceptual properties. It seems likely, that verbalizable tactile perceptual attributes might represent these interindividually comparable dimensions for vibration perception. Therefore, it can be concluded that vibration will be judged as plausible when its elicited perceptual attribute ratings are similar to the expected attribute ratings. For example, the better the relevant perceived properties (e.g. "up and down") match the expected properties of vibration in a scene (e.g. "driving on a cobblestone road") the more plausible it will be perceived. Thus, the Euclidean distance in the tactile perceptual attribute space between the expected attribute ratings and attribute ratings of presented vibration should be inversely correlated to the perceived plausibility of the presented vibration. Figure 2 depicts this relationship.

C. *Synthesizing vibration*

In order to translate tactile expectations into physical vibration parameters, the distance between the quantified, expected attribute ratings and known attribute ratings of previously rated vibration needs to be minimized in the 6-dimensional space of six chosen tactile attributes (see section II). The previously described dataset contains 107 generalized, parametric vibration stimuli, covering the level and frequency range of vibration encountered in everyday life. However, the just noticeable difference level (JNDL) for whole body vibration is approximately 1.5 dB [24] which is well below the difference between the two presented vibration levels of the dataset. Therefore, the dataset of attribute rating values was extended by linear interpolation between the two vibration levels in steps off approximately twice the JNDL. In a preliminary experiment with 4 vibration levels a linear relationship between vibration level and perceptual attribute ratings was confirmed in the level range of the stimuli in the dataset. The interpolation resulted in a database of 387 vibration stimuli as characterized by their vibration parameters and their corresponding attribute rating values in a range from 0 to 100. Thus, expectations quantified by ratings of the six attributes ("weak", "up and down", "tingling", "repetitive", "even", "fading") can be translated into physical vibration parameters ((peak-) level, (center/carrier-) frequency, bandwidth, modulation frequency, exponential decay constant). Since vibrations are selected to elicit perceptual attribute ratings most similar to expected ratings, they should be perceived as most plausible.



$$d(s,e) = \sqrt{\sum_{1}^{n}(e_i - s_i)^2} \sim \frac{1}{plausibility}$$

Figure 2. Plausibility can be interpreted as a similarity judgement between expectations and the presented stimulus. Thus it should be inversely correlated to the distance d between expections e and the presented stimuli s in the n-dimensional perceptual attribute space a. This hypothesized relationship is the basis for the synthesis approach.

TABLE II. In section III expected attribute ratings were assessed. Utilizing the proposed algorithm (section IV), attribute rating vectors were translated to vibration parameters by finding the perceptually most similar vibration in the database (section II).

Recorded Scenes			**Mean Expected Attribute Ratings**						**Translated Vibration Parameters**				
Number	***Speed***	***Surface***	***Weak***	***Up and Down***	***Tingling***	***Repetitive***	***Uniform***	***Fading***	***Sensation level***	***(Center / Carrier-) frequency***	***Band-width***	***Modula-tion fre-quency***	***Exponen-tial decay constant***
1	5 to 50	small cobblestone	39	43	30	56	50	46	26 dB	9 Hz			
2	30	small cobblestone	48	39	35	63	62	39	26 dB	9 Hz			
3	50	small cobblestone	40	45	37	61	53	55	26 dB	9 Hz			
4	5 to 50	cobblestone	16	73	45	54	25	73	36 dB	26 Hz	50 Hz		
5	30	cobblestone	20	70	48	64	29	69	33 dB	26 Hz	50 Hz		
6	50	cobblestone	17	74	41	61	34	73	36 dB	26 Hz	50 Hz		
7	50	tarmac (A-Road)	70	24	27	57	77	38	10 dB	7 Hz		2 Hz	
8	70	tarmac (A-Road)	74	12	24	56	82	21	17 dB	155 Hz		15 Hz	
9	5 to 50	tarmac	71	19	26	51	60	25	17 dB	9 Hz			
10	30	tarmac	75	19	23	52	73	26	10 dB	15 Hz		5 Hz	
11	50	tarmac	78	15	21	47	74	23	13 dB	155 Hz		15 Hz	
12	100	concrete motorway	62	19	29	62	75	29	23 dB	15 Hz			
13	100	surface change	72	19	26	31	74	23	13 dB	90 Hz			
14	40	tram tracks	32	64	23	38	27	55	30 dB	26 Hz	50 Hz		
15	50	expansion joint	39	60	20	18	25	50	26 dB	26 Hz	50 Hz		
16	100	expansion joint	67	17	31	35	73	28	20 dB	26 Hz			
17	30	manhole cover cobblestone	18	78	32	76	50	71	36 dB	9 Hz		2 Hz	
18	30	manhole cover tarmac	62	31	26	27	54	36	17 dB	201 Hz	400 Hz		
19	50	manhole cover tarmac	60	38	30	20	49	45	20 dB	201 Hz	400 Hz		

V. Comparison of the Plausibility of Recorded and Synthetic Vibration

A. *Experimental Design*

An experiment was conducted to compare the plausibility of the recorded vibration from section III to the plausibility of vibration synthesized according to section IV. It consisted of two separate sessions which were not presented on the same day to impede A/B comparison between recorded and synthesized vibration and to force a comparison to expectations instead. Test subjects were oblivious to the type of vibration (recorded vs. synthesized) presented. Similar to [25],they rated the perceived plausibility of the presented vibration in the context of the audio-visual-tactile scene on a rating scale [16] (see section III). All stimuli were presented in random order with the same test setup as in section III.

B. *Stimuli*

According to the approach proposed in section IV we identified the vibration parameter set in the database (section II) which was perceptually most similar to each scene's vibration, i.e. whose rating profile had the least distance to each scene's rating profile (section III) in the 6-dimensional perceptual attribute space (see TABLE II). Subsequently, these parameters were utilized to synthesize vibration for the duration of the complete scene for the quasi stationary scenes and for the duration of the impulse-like event for the impulse-like scenes. For the impulse-like scenes the recorded vibration was faded from/to zero before/after the impulse-like event for 0.3 s to enable comparison with the synthesized vibration.

C. *Subjects*

A total of 10 German laymen (5 male, 5 female) with an average age of 31 years (19 to 61 years) rated all stimuli.

D. *Results*

The results are shown in Figure 3. The plausibility ratings of synthetic and recorded vibration are very similar. Ratings were approximately normally distributed, as assessed by the Shapiro-Wilk-Test ($p > 0.05$). A repeated measures ANOVA was conducted which failed to reject the null hypothesis that there is no significant ($p > 0.05$) overall influence of vibration type (recorded vs. synthesized) for our dataset.

VI. Discussion

The results show that tactile expectations can be quantified by sensory tactile perceptual attribute ratings of six attributes: "weak", "up and down", "tingling", "repetitive", "even" and "fading". It is possible to synthesize whole-body vibration from these six attributes ratings. The perceived plausibility of

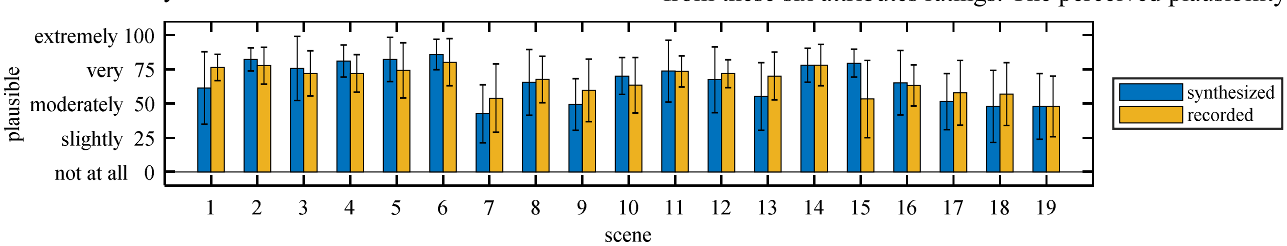


Figure 3. Mean plausibility ratings and standard deviations of the recorded and synthetic vibration in the context of their respective audio-visual scenes (see TABLE *II* for scene description)

the synthesized vibration is comparable to recorded vibration. Since the approach was demonstrated to be successful for various scenes with everyday life vibration, the results seem to be representative for whole-body vibration in general. Similar plausibility ratings despite temporal spectral differences between recorded and synthesized vibration suggest that an authentic reproduction of vibration is not necessary to elicit the plausibility illusion. This implies that vibration doesn't need to be perceptually indistinguishable from real vibration but rather needs to convey the relevant, expected sensory perceptual properties as sufficiently quantified by the six sensory perceptual attributes. The results suggest another implication of tactile feedback design: If it is sufficient to know the expected perceptual attribute ratings to create vibration that are perceived as plausible as original vibration in a given context, then long-term memory reliant tactile expectations likely do not contain more perceptual properties. Thus, the sensory short-term memory reliant A/B comparison method potentially overestimates tactile discrimination ability, for intuitive feedback vibration which is often not presented consecutively during product usage.

Future should examine the relationship between plausibility and varying distance in the perceptual attribute space. I can also attempt to generalize the implicit relationship between physical vibration parameters and sensory perceptual attributes into explicit regression models. The approach is likely transferable to other locations of excitation as suggested by the similar perceptual attribute ratings for whole-body and hand-arm vibration [13]. Furthermore, it should be verified that tactile expectations can be assessed directly from memory of test subjects without the necessity of presenting vibration or even any specific audio-visual context. The presented approach can be used to simplify tactile design, particularly for applications where a direct comparison is not needed or not possible. Especially for VEs a systematic plausible synthesis of vibration for VEs based on user expectations is feasible. Due to spectrally different stimuli mapping onto the same perceptual attribute ratings, a potentially simpler vibration reproduction system can be chosen, without compromising perceived plausibility. The general approach might also be useful in the context of product design, because it is possible to systematically elicit commonly known perceptual attributes which are intuitively understandable to laymen and do not require prior training.

Acknowledgment

This study was supported through DFG AL1473/5-1.

References

[1] U. Jekosch, “Basic Concepts and Terms of ‘Quality’, Reconsidered in the Context of Product-Sound Quality,” *acta acustica united with Acustica*, vol. 90, no. 6, pp. 999–1006, 2004.

[2] M. Slater, “Place Illusion and Plausibility Can Lead to Realistic Behaviour in Immersive Virtual Environments,” *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 364, no. 1535, pp. 3549–3557, 2009.

[3] W. W. Gaver, “How Do We Hear in the World? Explorations in Ecological Acoustics,” *Ecological psychology*, vol. 5, no. 4, pp. 285–313, 1993.

[4] W. W. Gaver, “What in the World Do We Hear? An Ecological Approach to Auditory Event Perception,” *Ecological psychology*, vol. 5, no. 1, pp. 1–29, 1993.

[5] O. Schneider, K. MacLean, C. Swindells, and K. Booth, “Haptic experience design: What hapticians do and where they need help,” *International Journal of Human-Computer Studies*, vol. 107, pp. 5–21, 2017.

[6] S. Guest, J. M. Dessirier, A. Mehrabyan, F. McGlone, G. Essick, G. Gescheider, A. Fontana, R. Xiong, R. Ackerley, and K. Blot, “The development and validation of sensory and emotional scales of touch perception,” *Attention, Perception, & Psychophysics*, vol. 73, no. 2, pp. 531–550, 2011.

[7] S. Okamoto, H. Nagano, and Y. Yamada, “Psychophysical Dimensions of Tactile Perception of Textures,” *Haptics, IEEE Transactions on*, vol. 6, no. 1, pp. 81–93, 2013.

[8] H. Seifi, K. Zhang, and K. E. MacLean, “VibViz: Organizing, visualizing and navigating vibration libraries,” in *World Haptics Conference (WHC), 2015 IEEE*, 2015, pp. 254–259.

[9] H. Seifi and K. E. MacLean, “Exploiting haptic facets: Users’ sensemaking schemas as a path to design and personalization of experience,” *International Journal of Human-Computer Studies*, vol. 107, pp. 38–61, 2017.

[10] I. Hwang and S. Choi, “Perceptual space and adjective rating of sinusoidal vibrations perceived via mobile device,” in *Haptics Symposium, 2010 IEEE*, 2010, pp. 1–8.

[11] G. Park and S. Choi, “Perceptual space of amplitude-modulated vibrotactile stimuli,” in *World Haptics Conference (WHC), 2011 IEEE*, 2011, pp. 59–64.

[12] J. Blauert and U. Jekosch, “Sound-quality evaluation–a multi-layered problem,” *Acta acustica united with acustica*, vol. 83, no. 5, pp. 747–753, 1997.

[13] R. Rosenkranz, S. Gruschwitz, M. Wilberg, M. E. Altinsoy, and S. Merchel, “Identification and Evaluation of Perceptual Attributes for Periodic Whole-Body and Hand-Arm Vibration,” in *IEEE Euro Haptics 2018*, 2018.

[14] M. Morioka and M. J. Griffin, “Absolute Thresholds for the Perception of Fore-And-Aft, Lateral, and Vertical Vibration at the Hand, the Seat, and the Foot.,” *Journal of Sound and Vibration.*, vol. 314, pp. 357–370, 2008.

[15] ISO2631, “Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration,” International Organization for Standardization, Geneva, Switzerland, 1978.

[16] B. Rohrmann, “Verbal qualifiers for rating scales: Sociolinguistic considerations and psychometric data,” *University of Melbourne, Melbourne2007*, 2007.

[17] R. Rosenkranz, S. Gruschwitz, M. E. Altinsoy, and S. Merchel, “Wahrnehmungsmerkmale von breitbandigen Ganzkörperschwingungen im Vergleich zu sinusoidalen Ganzkörperschwingungen,” in *DAGA 2016 - 42th German Annual Conference on Acoustics*, 2016.

[18] M. E. Altinsoy, U. Jekosch, J. Landgraf, and S. Merchel, “Progress in Auditory Perception Research Laboratories - Multimodal Measurement Laboratory of Dresden University of Technology,” in *Audio Engineering Society Convention 129*, 2010.

[19] M. E. Altinsoy and S. Merchel, “BRTF (Body-Related Transfer Function) and Whole-Body Vibration Reproduction Systems,” in *Audio Engineering Society Convention 130*, 2011.

[20] P. Novo, “Auditory Virtual Environments,” in *Communication Acoustics*, J. Blauert, Ed. Springer, 2005, p. 278.

[21] G. Calvert, C. Spence, and B. E. Stein, *The Handbook of Multisensory Processes*. The MIT Press, 2004.

[22] A. Israr, S. Zhao, K. Schwalje, R. Klatzky, and J. Lehman, “Feel Effects: Enriching Storytelling with Haptic Feedback,” *ACM Trans. Appl. Percept.*, vol. 11, no. 3, pp. 11:1–11:17, 2014.

[23] C. Kuhn-Rahloff, *Realitätstreue, Natürlichkeit, Plausibilität: Perzeptive Beurteilungen in der Elektroakustik*. Springer-Verlag, 2012.

[24] M. Morioka and M. J. Griffin, “Difference Thresholds for Intensity Perception of Whole-Body Vertical Vibration: Effect of Frequency and Magnitude,” *The Journal of the Acoustical Society of America*, vol. 107, no. 1, pp. 620–624, 2000.

[25] Z. Wang, J. Lu, A. Peer, and M. Buss, “Influence of Vision and Haptics on Plausibility of Social Interaction in Virtual Reality Scenarios,” in *Haptics: Generating and Perceiving Tangible Sensations*, 2010, pp. 172–177.