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HEARING WITH YOUR BODY: THE INFLUENCE OF WHOLE-BODY VIBRATIONS ON LOUDNESS PERCEPTION

Sebastian Merchel, Anna Leppin and Ercan Altinsoy

Chair of Communication Acoustics, Dresden University of Technology, 01062 Dresden, Germany
e-mail: sebastian.merchel@tu-dresden.de

Knowledge of the interaction of the tactile and auditory sense is necessary for e.g. creating virtual environments or product design. In every day life auditory perception is often coupled to tactile perception. Just think of someone knocking on a door, driving a car or of the bass felt in the stomach during a rock concert.
In this study, the influence of vertical whole-body vibrations on loudness perception is investigated. To present the whole-body vibrations, an electrodynamic shaker and chair system is used. The auditory stimulus is presented diotically through a pair of closed dynamic headphones. The vibration reproduction system was individually calibrated for each of the test persons. Then, the individual perception thresholds for whole-body vibrations have been measured. To mask possible sound generated by the vibration reproduction system, pink noise was played back through the headphones.
A loudness matching experiment with 10 test persons was carried out. In this experiment, an acoustic stimulus was presented first without tactile stimulation and then together with a vibratory stimulus. The test persons' task was to adjust the level of the acoustic stimulus which was played simultaneously with a vibratory stimulus until it was perceived as equally loud as the acoustic stimulus without tactile stimulation. The loudness matching experiments were carried out for four sinusoidal tones. The frequencies 10, 20, 63 and 200 Hz were chosen to stimulate different tactile receptors. Three different vibration levels (4, 8 and 12 dB above individual vibration threshold) were used to study the influence of the vibration amplitude. The statistic analysis of the results indicates that whole-body vibrations have a significant influence on loudness perception. If an acoustic stimulus is accompanied by a vibratory stimulus, the level of the acoustic stimulus is on average perceived one decibel higher. Surprisingly, this effect is independent of the vibration level.

1. Introduction

The human being perceives its environment with all five senses at the same time. A coherent image of this environment emerges first when the different sensory impressions are connected with each other. Perception is a multi-sensory phenomenon where the individual sensory modalities interact. Understanding this interaction of different sensory modalities is important for designing virtual realities or for the product design in entertainment or automotive industry[1]. In this paper, one of these interactions – the influence of whole-body vibrations on human loudness perception – will be discussed. The hypothesis that acoustic signals are rated as louder when additionally whole-body vibrations are present is going to be examined.

2. Recent Studies

In this section, a survey of selected studies concerning the influence of vibration on loudness perception will be given, considering neurological as well as psychophysical studies.

2.1 Neurological Studies

A study by Kayser[2] on narcotized Rhesus monkeys has proved integration effects of auditory and tactile signals near the primary auditory cortex. Kayser observed an increased integration effect when the signals are temporally coincident as well as the effect of inverse effectiveness. The principle of inverse effectiveness states that the stimulus integration of two senses is the stronger the less intense the constituent stimuli are. From the early integration near the auditory cortex, while the monkeys are anaesthetized, the authors deduce the pre-attentive *bottom-up* mechanism during the audio-tactile integration.

In a study, Foxe[3] proves audio-tactile integration to be present already during early phases of stimulus processing in the cerebral cortex of the human being. In the course of this, supra-additive integration effects of auditory and tactile stimulation were detected in a subregion of the auditory cortex. This means, that the observed action potential during simultaneous auditory and vibratory stimulation exceeds the sum of the detected action potential when stimulating first one and then the other. Further studies[4,5] prove, that the somatosensory cortex (SI and SII) as well as the auditory cortex are stimulated through tactile stimuli. This indicates that the auditory and tactile stimuli are integrated already in an early phase in a *feed-forward* process and therefore interact.

The strength of the stimulus being observed in the brain can provide information about the general integration of two modalities. The proof of the integration of auditory and tactile stimuli on the basis of action potential, however, gives no information about the kind of integration, e.g. if loudness or comfort are influenced.

2.2 Psychophysical Studies

Schürmann[6] proves the direct influence of hand vibrations on loudness perception. In this study, audio-tactile stimuli are perceived 12.4 % louder as purely auditory stimuli. This equals a sound pressure level difference of 1.1 dB.

Bellmann[7] as well as Lange[8] could not find an influence of whole-body vibrations on loudness perception. Bellmann determined only a slight difference (max. 0.5 dB) while measuring the 60 Hz loudness contour with and without additional vibration. However, the inter-individual variances increased from 5-7.5 dB to 6-9.5 dB.

Lange investigated the influence of vibration on loudness perception by means of sinusoidal and broadband signals (automotive noises). There also no greater differences than 0.5 dB SPL were found. He notes that experienced test persons may rate the vibro-acoustic signals hypercritically. This might be due to their expectations, that audio-tactile signals are louder.

The mentioned studies differ from each other in view of the applied measurement methods and the used stimuli. These very different results regarding literature give reason for again measuring the influence of vibrations on loudness perception within this study. Additionally, influencing variables like vibration frequency and vibration amplitude are to be investigated.

3. Experiment

3.1 Test Persons

Altogether, 28 test persons (12 female, 16 male) took part in the experiment. The average age was 27.3 years (19 – 52 years). All test persons had not been involved in psychophysical experiments before. They were not informed about the topic of this study.

3.2 Test Setup

Figure 1 shows the general measurement setup. The vibration chair, which reproduces the whole-body vibration, is placed in a soundproof booth. The audio signals are outputted via an external Hammerfall DSP Multiface sound card, amplified by a Phone-Amp G93 and reproduced via a pair of Sennheiser HDA 200 closed dynamic headphones.

The vibration signals are also outputted via the external sound card and amplified with an Alesis RA150 amplifier. The acceleration signals perceived by the test person on the surface of the vibration chair can be triaxially measured with a vibration pad (B&K Type 4515B) and a Sinus Harmonie quadro measuring board.

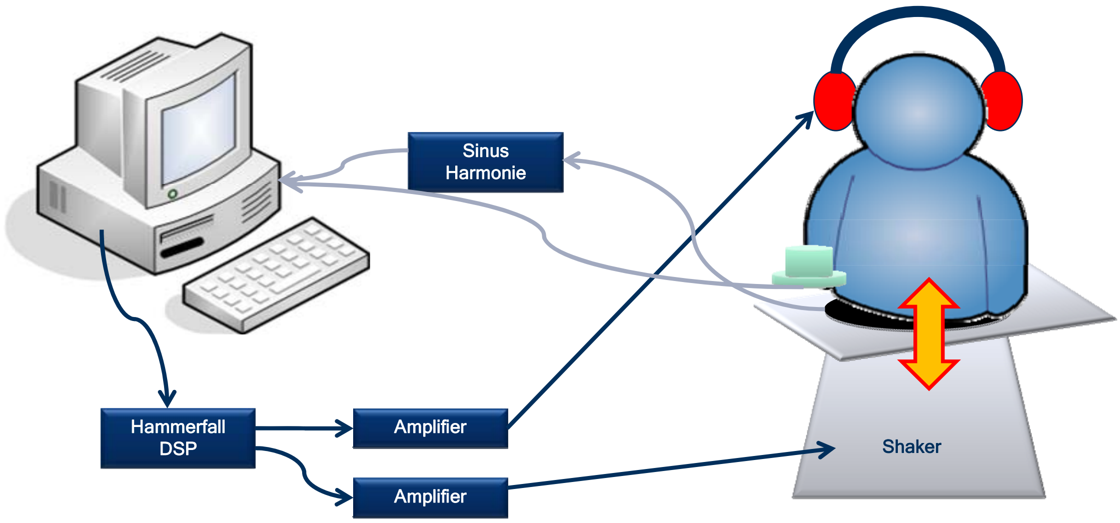

Figure 1. Experimental test setup with test person sitting on the vibration chair wearing headphones.

As input device for the test person a PowerMate is applied. This control knob has no stop, no optical marks and is infinitely adjustable. Thus, the test person has to concentrate completely on the rendered signals and, particularly when turning the knob several times, the person does not have any clue in which direction and how far the knob already has been turned. For this test, the control knob is used like the volume control of a stereo, but controlling the vibration amplitude.

3.2.1 Calibrating the Vibration Chair

The transfer characteristic of the vibration chair depends to a great extend on the individual body properties, e.g. weight, body mass index, adipose. This frequency response depending on the individual test person is called the Body Related Transfer Function (BRTF)[9]. To compensate the BRTF a calibration was implemented to inversely pre-filter the vibration signals for every individual test person. Before each experimental trial, the vibration chair was calibrated again.

3.2.2 Acoustic Emission of the Vibration Chair

Once the frequencies increase, the vibration chair can emit acoustic noise. The perception of this noise cannot be completely suppressed through the closed headphones. To acoustically mask the noises emitted by the chair pink noise, presented at 74 dB(A), was chosen.

3.3 Stimuli

In natural situations, the signal forms of auditory and tactile stimuli produced through the same event are similar to each other. The sound produced by stroking a piece of paper with the hand as well as the tactile stimulus both have the typical broadband frequency characteristic of noise, whereas the sounds of an organ and the vibrations felt when sitting on a church bench are sinusoidal. To detect a possible integration of vibratory and auditory stimuli, it therefore makes sense to choose the same signal form for both kinds of stimuli.

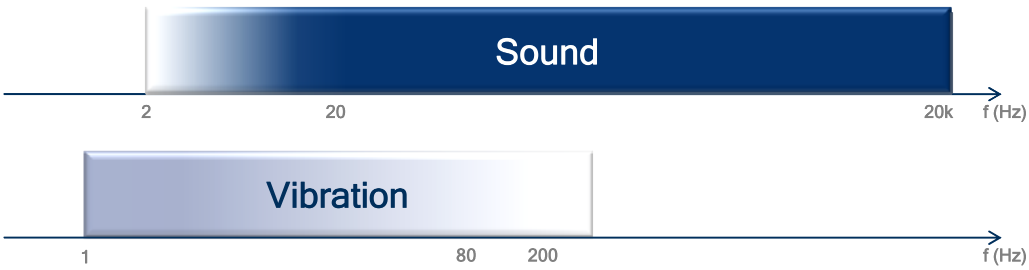

Figure 2. Overlapping frequency domains for acoustic oscillations and whole-body vibrations perceivable by the human being.

Figure 2 shows the frequency domains in which sound and whole-body vibrations are perceived. It can be seen that the frequency bands overlap below 300 hertz. Even though the threshold of hearing is said to have its lowest frequency level at 20 Hz, people with normal hearing are also able to perceive frequencies lower than 20 Hz, provided the sound pressure levels are high enough. The absolute threshold of hearing for e.g. ten hertz is at around 100 dB SPL[10]. The frequencies 10, 20, 63 and 200 hertz are chosen. The choice is made in a way, so that in each case a maximum of two kinds of tactile receptors are addressed (see Fig. 3). Thus, the lowest frequency range for perceiving auditory stimuli, as well as the highest frequency range for perceiving whole-body vibrations is covered.

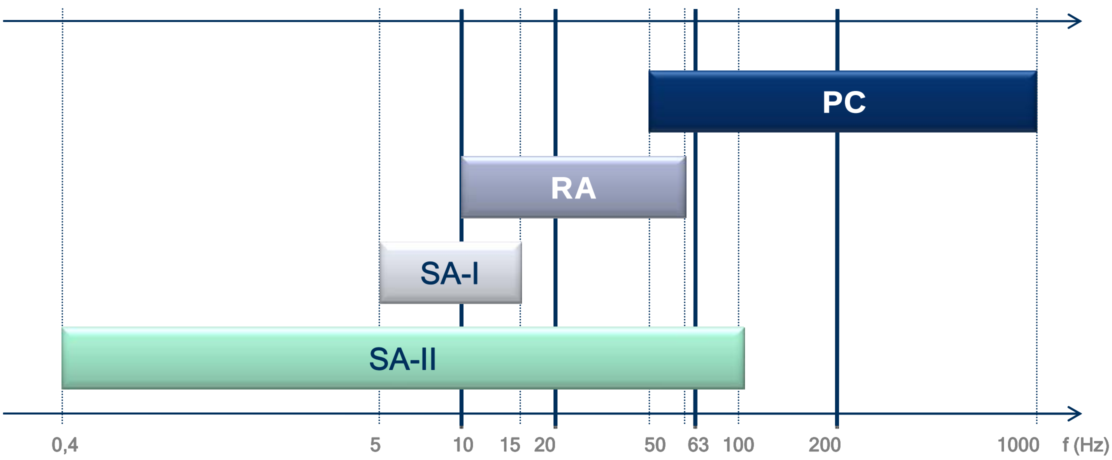

Figure 3. Frequency domains of the different mechanoreceptor types (Pacinian corpuscle PC, Meissner's corpuscle RA, Merkel's discs SA-I, Ruffini ending SA-II) of the human being[11]. Additionally, the four chosen stimulus frequencies are marked.

To achieve comparable results with different frequencies, the acoustic and vibration levels should remain constant in relation to a reference point. The simplest constant parameter seems to be a constant sound pressure level or a vibration level. However, not all sounds with the same sound pressure level but a different frequency are perceived as equally loud. Thus, equal-loudness contours have been defined for acoustic signals in the ISO 226[12]. Curves for acceleration levels perceived with the same intensity are also determined for whole-body vibrations. Already while measuring the perception thresholds, great inter-individual differences occur. Since only relatively low levels above the perception threshold are to be tested, a reference to the perception threshold seems to be appropriate. For this purpose, Bellmann[7] as well as Lange[8] used self-measured averaged thresholds. Because of the great inter-individual differences in the perception threshold, individual perception thresholds regarding vibration are determined for the chosen frequencies in this study. For being able to analyze in which way the vibration amplitude influences loudness perception, vibration amplitudes are generated with four, eight and twelve decibel above the individual perception threshold.

The acoustic reference tone has a constant sound pressure level of 10 dB above the individual detection threshold in pink noise, with a level of 74 dB(A). Therefore, it is also necessary to determine the detection threshold of sinusoidal tones in pink noise for the chosen frequencies.

3.4 Experimental Methods

3.4.1 Individual Perception Thresholds

An adaptive 3AFC 1up-2down method is used for determining the perception thresholds of the vibration, as well as for measuring the detection thresholds of the sinusoidal tones in pink noise. In Fig. 4 one trial of measuring the perception threshold is displayed.

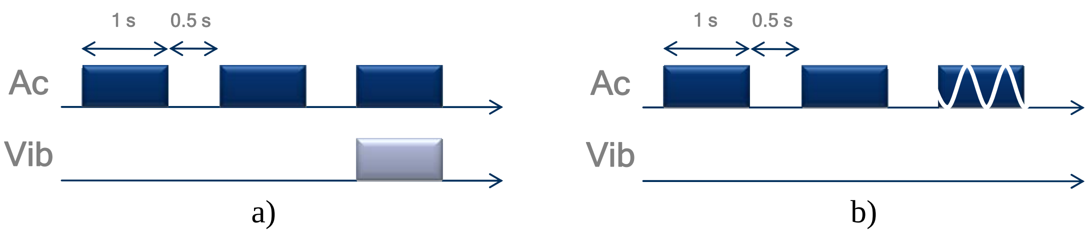

Figure 4. One trial of measuring the perception threshold via 3AFC proceeding for a) whole-body vibrations and b) sinusoidal tones in pink noise.

3.4.2 Loudness Matching

To investigate the influence of the vibration on loudness perception, the test person is to compare a reference tone without vibration with a test tone which is reproduced simultaneously with a vibration. During this process, the level of the test tone changes. When the test person values both of the tones as equally loud, the loudness matching experiment is completed.

For the loudness matching experiment the method of adjustment is used. One trial of the loudness matching experiment is displayed in Fig. 5. The reference tone without vibration and the test stimulus with vibration are played back, in turns. They are one second long and divided from each other through half-second brakes. The test person can influence the amplitude of the test stimulus via the control knob, while the vibratory stimulus remains constant. When the test person thinks that both of the tones are equally loud, she/he can finish the test by clicking on the knob. The loudness matching is carried out for each of the three vibration amplitudes and the four frequencies, and is repeated ten times for each subject.

Additionally, a purely acoustical reference loudness matching is carried out, comparing a test tone without vibration with the reference tone without vibration.

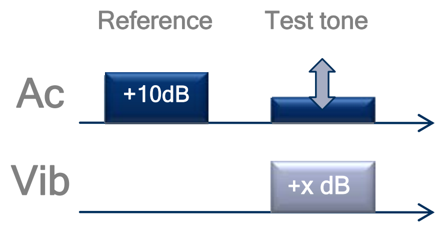

Figure 5. One trial of the loudness matching experiment. The test person can change the amplitude of the acoustic test tone (with vibration) via the control knob, until she/he considers the tone to be as loud as the acoustic reference tone (without vibration). The amplitude of the reference tone is adjusted at 10 dB above the detection threshold in pink noise.

4. Results

4.1 Individual Perception Thresholds

Figure 6 shows the test persons' perception thresholds. The average perception threshold and standard deviation are shown in black. The comparison of the average values, which are determined in this study, with the ones determined by Bellmann[13] shows that for 10, 20 and 63 Hz the values are very much alike. Reaching 200 Hz, the average perception thresholds considerably deviate from each other. While with Bellmann the perception threshold stays nearly the same, the threshold measured here is around seven decibel higher. For all but two test persons the perception threshold increased from 63 Hz to 200 Hz. Measurements of Morioka and Griffin[14], however, confirm a higher perception threshold for 200 Hz then for 63 Hz. It is very obvious, that the average perception threshold hardly approximates the individual perception thresholds. For all but one test person the deviations for each of the four frequencies are above the just noticeable difference in level of 1.5 dB. The great inter-individual differences between the perception thresholds of the individual test persons support the decision, that the perception threshold should be individually determined for each of the test persons.

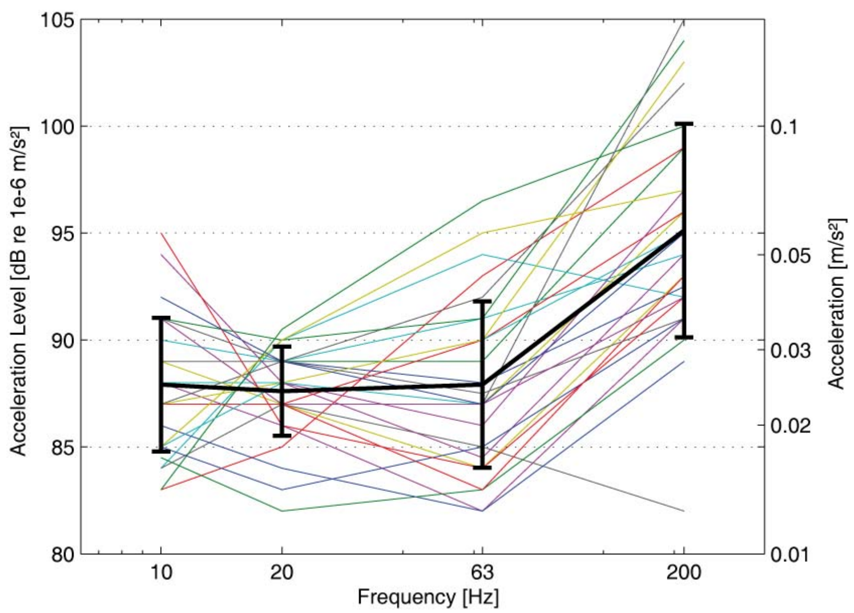

Figure 6. Perception thresholds of each of the test persons. The average perception threshold with standard deviation is charted in black.

The measured auditory perception thresholds are in accordance with the literature and are not going to be discussed here.

4.2 Loudness Matching Experiment

Figure 7 displays the average values as well as the standard deviations for the differences of the loudness matching. If no additional vibration is rendered (no Vib), on average a level difference of 0 dB between reference tone and adjustable test tone can be observed. Rendering the test tone together with a vibration, the test tone, on average, is adjusted one decibel lower. Furthermore, the difference of the adjusted sound pressure level also changes with frequency.

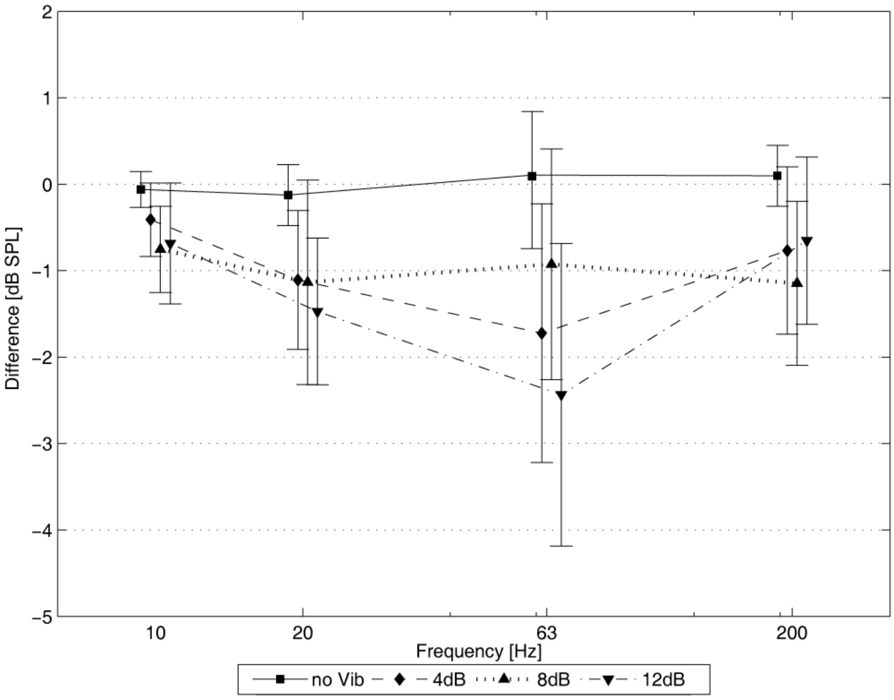

Figure 7. Average values and standard deviations of the results of the loudness matching (differences between reference tone level and test tone level, which was perceived as equally loud) for each of the three different vibration amplitudes and without vibration.

5. Discussion

5.1 The Influence of the Acceleration Level

The influence of the acceleration level on loudness perception is statistically significant ($p<0,001$). The average differences between reference tone level and test tone level for the different acceleration levels are displayed in Table 1. Significant differences are marked with an asterisk. It becomes apparent, that additionally reproducing a vibration has a significant influence on the loudness perception of the test person, whereas the value of the acceleration level does not induce a significant difference. The increased loudness perception can not be explained with possible bone conducted vibration, which interferes with the acoustic stimulus. This would cause that the value of the acceleration level should influence the loudness matching. As this is not the case, an integration effect is suggested.

Table 1. Pair wise comparison of the tone level differences (dB SPL) during the loudness matching for the different acceleration levels: statistically significant differences are marked with an asterisk ($p<0.05$).

	no Vib	4 dB	8 dB	12 dB
no Vib		1,1*	1,1*	1,4*
4 dB			0,0	0,3
8 dB				0,3
12 dB				

At a first glance, a difference of 1 dB sound pressure level may appear relatively little. However, the dynamic range of the auditory system decreases with decreasing frequency. Thus, a small increase in level can change the perceived loudness from barely perceivable to loud[10].

The results of this study essentially deviate from the results of Bellmann[7] and Lange[8], who could not prove whole-body vibrations to have an influence on the loudness perception. Compared to Schürmann[6], the observed effect is of the same dimension. There are several possibilities to explain, why the results of this study deviate from some results in the literature:

- Experienced test persons may judge loudness hypercritically compared to inexperienced ones. In this study inexperienced test person were used.
- More exact measurement due to referring the acceleration level to the individual perception thresholds.
- Using the method of adjustment with a marker less infinite rotary knob.
- The greater influence of the vibration on the loudness perception may be traced back to the broadband masking, as multi-modal neurons are increasingly stimulated by complex sounds like noise, the clattering sound of a bunch of keys or the sound of crumbling paper. However, the multi-modal neurons may not be stimulated by pure tones[15].

5.2 Influence of Frequency

The vibration at a frequency of 63 Hz – in comparison to the other considered frequencies – has a stronger effect on the loudness perception, as can be seen in Fig. 7. As the standard deviation of the results is very high, the influence of the frequency on the loudness matching is hardly not statistically significant ($p>0.05$). The reasons for bigger standard deviations at 63 Hz are not clear yet.

6. Summary and Perspectives

Within the scope of this work, the assumption that an acoustic signal is perceived as louder, when additionally whole-body vibrations are reproduced, was investigated. It was proved that whole-body vibrations are significantly influencing loudness perception. When reproducing tones embedded in noise and simultaneously reproducing whole-body vibrations, tones are on average perceived to be one decibel louder. No essential differences of the effect depending on the applied acceleration level of the vibration could be detected. There are different reasons, why the results of this work deviate from the results of previous studies, e.g. referring the acceleration level to the individual perception threshold, applying the method of adjustment as psychoacoustic measuring method, using broadband acoustic signals and carrying out the experiment exclusively with inexperienced test persons.

The reasons have to be analyzed during further experiments. Thus, it is to be investigated in which way higher acceleration levels influence loudness perception. If using an essentially higher acceleration level does not show a significant influence, an adequately high acceleration level that is perceived by each of the test persons, can be chosen for further research. Furthermore, the influence of the psychoacoustic measurement method is to be checked and the results are to be verified, e.g. with an adaptive up-down loudness matching experiment. The impact of complex signals on audio-tactile integration should be investigated for acoustic, as well as for vibratory signals.

7. Acknowledgement

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