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Tactile Intensity Perception Compared to Auditory Loudness Perception

Sebastian Merchel, M. Ercan Altinsoy and Anna Schwendicke[1]

***Abstract*— The examination of auditory intensity perception has a long history, and comprehensive knowledge exists. However, tactile intensity perception has not been studied as thoroughly. A short literature review provides an overview of the current state of research, with a focus on perceived vibration magnitude. To broaden our knowledge, tactile intensity perception was investigated further in this study. The growth of perceived intensity of seat vibrations with increasing vibration level was compared to auditory loudness. Therefore, a magnitude estimation experiment was performed. Curves of equal vibration intensity have been determined.**

I. INTRODUCTION

In real life sound and vibrations are often perceived simultaneously. For example, while sitting in a car, a passenger is exposed to different forms of vibrations and noise. Similarly, seats in a concert hall or a church vibrate during concerts [1]. Vibrations can be perceived at up to several hundred hertz through the tactile sense (mechanoreceptors in the skin). Simultaneously, sound is heard via the auditory system down to a lower limiting frequency of approximately 20 Hz. There is considerable overlap between the frequency ranges of both sensory systems. The question is raised whether the intensity perception of vibrations and sound is similar. Understanding similarities and differences is important for the design of multimodal user experiences, e.g., in the automotive industry or for multimodal music reproduction systems [2], [3], [4].

The state of research regarding auditory and tactile intensity perception will be summarized in the following. Subsequently, the perceived vibration magnitude will be measured as a function of sensation level using a broad frequency range and a large amplitude range. This study focuses on seat vibrations, such as the vibrations that can be perceived in a vehicle or church. A common measurement unit for vibrations is the acceleration level L_{acc}. It is defined as the logarithmic ratio of the acceleration a and a reference value $a_0 = 1\,\mu\mathrm{m/s}^2$. In contrast to sound pressure level, 0 dB acceleration level is not related to the perception threshold.

$$L_{\mathrm{acc}} = 20\,log\frac{a}{a_0}\,\mathrm{dB}$$

A. Auditory Intensity Perception

The perceived magnitude in audition is referred to as loudness. Stevens proposed the sone as the unit of loudness [5]. The relationship between sensation and physical stimuli can be described by Stevens' power law [6], which states that the sensation magnitude Ψ grows as a power function of the physical stimulus magnitude ϕ:

$$\Psi = k\phi^n. \tag{1}$$

The constant k changes depending on the units of measurement. More interestingly, the value of the Stevens' exponent n is characteristic for each sensory modality. The power law can be extended using an additive constant ϕ_0, which represents the perception threshold [7]:

$$\Psi = k(\phi - \phi_0)^n. \tag{2}$$

If plotted with logarithmic scales on both axes, the power function becomes a straight line. For loudness perception, Stevens' exponent depends on frequency. At 1 kHz, this exponent was observed to be approximately 0.6, which corresponds to an increase of 10 dB in sound pressure level per doubling of loudness. However, for lower frequencies or low sensation levels, the perceived magnitude grows more rapidly. This relationship is illustrated for a tone with 250 Hz in Fig. 1 using data from Hellman and Zwislocki [8].

B. Tactile Intensity Perception

Stevens' exponent for perceived vibration magnitude depends on the stimulated body site. An example for stimulation at the finger and volar arm is plotted for 250 Hz in Fig. 1, according to Verrillo and Chamberlain [9]. A 0.28 cm^2

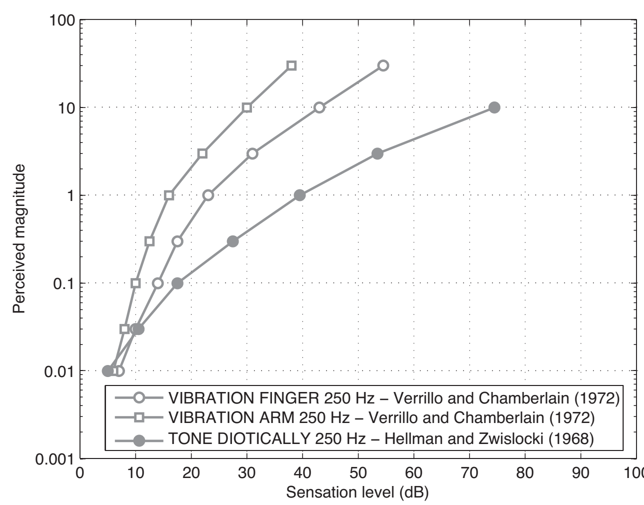

Fig. 1. The growth of perceived magnitude as a function of sensation level for acoustical and vibratory stimuli at 250 Hz. The acoustical stimulus was reproduced diotically via earphones [8]. Vibrations were reproduced at the finger and forearm using a 0.28 cm^2 contactor [9]. All of the studies plotted here used the method of numerical magnitude balance.

[1]All authors are with Department of Communication Acoustics, Dresden University of Technology, 01062 Dresden, Germany sebastian.merchel@tu-dresden.de

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contactor was used in both cases. Stevens' exponent is higher for vibrations at the arm compared to the finger. It was hypothesized that this growth would be slightly more rapid for body sites with a lower density of neural innervation. This inverse dependence has also been reported for other regions of the body, such as the forearm compared to the thigh [10]. However, it could also be supposed that the rate of growth is inversely correlated with 'the total number of sensory neural units stimulated rather than being related simply to the density of neural innervation' [9].

Seat and whole-body vibrations have been investigated mainly in the contexts of discomfort, annoyance, and health risk estimation. Thus, most examinations have considered high vibration magnitudes and low frequencies. For clarity, this comparison will concentrate solely on seat vibrations in the vertical direction. Controversial data exist regarding the *perceived magnitude* of sinusoidal vibrations for subjects seated on rigid seats. Widely varying Stevens' exponents have been reported, ranging from 0.46 to 1.75 [11], [12], [13], [14], [15]. The variation in the data might be due to varying experimental procedures and the different ranges of vibration intensities investigated. Miwa [11] reported an exponent of 0.46 for vertical vibrations between acceleration levels of 107 dB and 147 dB at 5, 20, and 60 Hz. He used the corrected ratio method, which consists of two experiments based on fractionation and equisection judgments. Jones and Saunders [12] investigated the subjective response to vertical vibrations between 5 and 40 Hz. They used a magnitude estimation procedure and obtained an exponent of 0.93. Using cross-modality matching techniques, Hempstock and Saunders [13] investigated the subjective growth of whole-body vertical sinusoidal vibrations between acceleration levels of 114 and 136 dB. Frequencies between 5 and 80 Hz were used. They found exponents between 0.49 and 1.42, that were greatly influenced by the applied method. Using the method of magnitude production and magnitude estimation, Fothergill and Griffin [14] obtained an exponent as high as 1.75 for a 10 Hz vibration and acceleration levels between 110 and 125 dB. Despite their contradictory results, none of the studies directly measured the perceived vibration intensity close to the threshold. Unfortunately, there are no data available for frequencies greater than 80 Hz.

Some studies exist, which did not investigate the perceived intensity directly. For instance, Howarth and Griffin [15] examined the *annoyance* for frequencies between 4 and 63 Hz using magnitude estimation. They reported a mean exponent of 1.2 for acceleration levels between 92 and 112 dB. Morioka and Griffin [16] asked their test participants to estimate the perceived *discomfort* of seat vibrations over a broad dynamic range. They measured relatively low Stevens' exponents and hypothesized that there would be a frequency dependence. A decrease of the exponent with increasing frequency from 16 Hz ($n \approx 0.8$) to 100 Hz ($n \approx 0.4$) was reported. However, it is unclear whether (dis-)comfort or annoyance can be compared with perceived vibration magnitude.

Therefore, the growth of perceived intensity for vertical seat vibrations will be investigated in the following using a broad range of frequencies (10 to 200 Hz) and amplitudes from hardly perceivable to annoying.

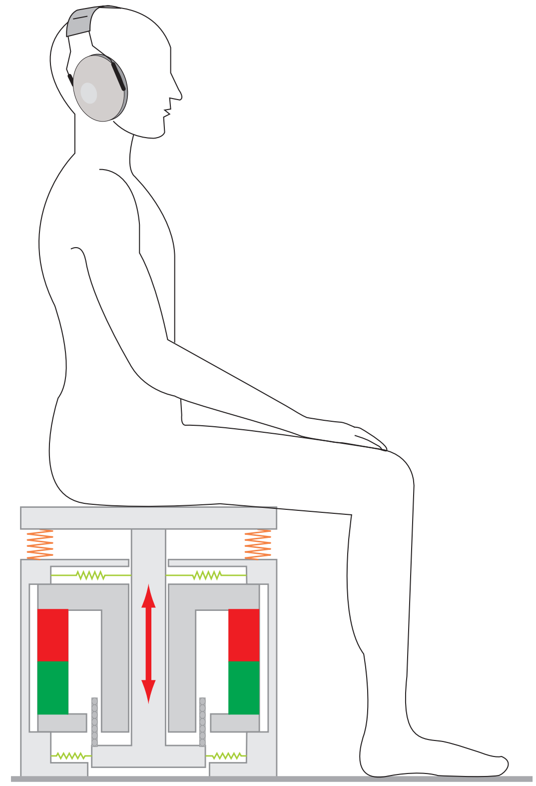

Fig. 2. Vibration chair with electrodynamic exciter.

II. Setup

A. Vibration Reproduction

Seat vibrations were generated using an electrodynamic shaker (self-made, based on an RFT Messelektronik Type 11076 with an Alesis RA 150 amplifier). Vibrations were reproduced vertically, as shown in Fig. 2.

The subjects were asked to sit on a flat, hard wooden seat (46 cm × 46 cm) with both feet flat on the ground. If necessary, plates were placed beneath the subjects feet. The transfer characteristic of the vibrating chair (relation between acceleration at the seat surface and input voltage) was strongly dependent on the individual person. This phenomenon is referred to as the body-related transfer function (BRTF). Differences of up to approximately 10 dB have been measured for different subjects [17]. Considering the just-noticeable difference in thresholds for vertical whole-body vibrations, which is approximately 1 dB [18], [19], [20], the individual BRTFs should be compensated for during perceptional investigations. The BRTF of each subject was individually monitored and equalized during all experiments. Subjects were instructed not to change their sitting posture after calibration until the end of the experiment. The transfer functions were measured using a vibration pad (B&K Type 4515B) and a Sinus Harmonie Quadro measuring board, and they were compensated for using inverse filters in Matlab.

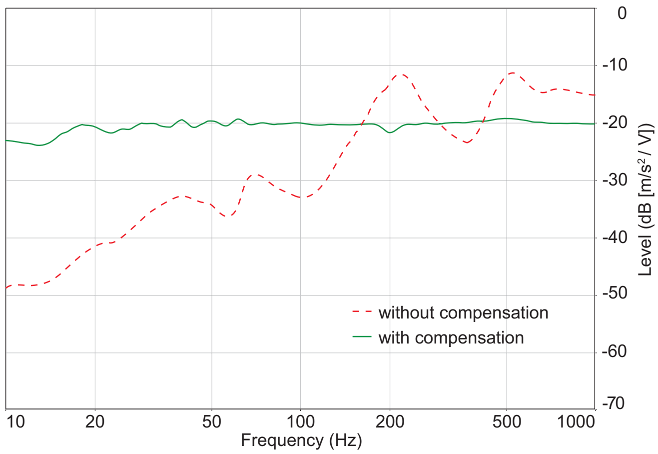

Fig. 3. Body-related transfer functions (65536-point FFT, 1/24th octave intensity averaging) measured at the seat surface of the vibration chair, with and without compensation.

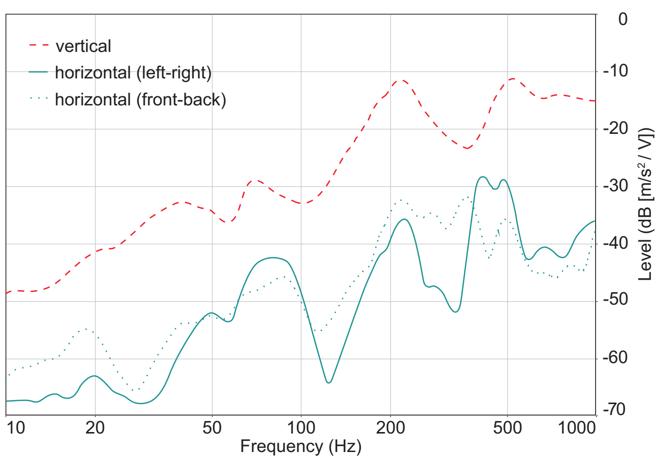

Fig. 4. Crosstalk between the vertical and horizontal vibration axes for body-related transfer functions (65536-point FFT, 1/24th octave intensity averaging) of the vibration chair.

This procedure resulted in a flat frequency response over a broad frequency range (±2 dB from 10 to 1,000 Hz). An exemplary BRTF, with and without individual compensation, is shown in Fig. 3.

Although the frequency response in the vertical direction is interesting, the crosstalk to the horizontal vibration axis must also be considered. This crosstalk was minimized using hard, nonslotted disk springs to center the shaker. This configuration has the disadvantage that high power is needed to drive the shaker; however, more than a -10 dB difference in the acceleration levels between vibrations in the vertical and horizontal directions could be achieved over a broad frequency range. The resulting crosstalk between shaker axes is shown in Fig. 4. The remaining crosstalk might not be crucial because the perception threshold for horizontal seat vibrations is approximately 10 dB higher than for the vertical direction [21].

B. Audio Reproduction

An external Hammerfall DSP Multiface II sound card and a Phone-Amp G93 was used for audio reproduction. Pink noise was presented through a set of closed dynamic headphones at 74 dB(A) to acoustically mask possible sound radiation from the shaker. Sennheiser HDA 200 headphones were selected to additionally attenuate airborne sound passively. The passive attenuation at 100 Hz was approximately 14 dB and increased toward higher frequencies.

III. Subjects

Ten subjects (eight male and two female) voluntarily participated in the study without compensation. Most of the participants were students between 20 and 27 years old (mean = 23 years). The participants weighed between 62 kg and 83 kg (mean = 73 kg) and had no hearing or spinal damage.

The subjects were instructed to sit upright in a comfortable posture with their hands on their thighs and both feet flat on the ground. Additional plates were used to adjust the height of the feet until the thighs were approximately horizontal and level with the seat.

IV. Stimuli and Experimental Design

The subjects were asked to sit upright on the vibration chair and to remain in the same position throughout the experiment. The test participants were asked to judge the intensity of the seat vibration at each of the selected frequencies (10, 20, 50, 100, 150, and 200 Hz). The vibrations varied in acceleration level from 90 to 130 dB in 5 dB steps. The range of stimulus magnitudes was extended to 140 dB for 100, 150, and 200 Hz to account for the rising perception threshold at higher frequencies. All of the vibration signals were faded in and out using ramps of 50 ms with the shape of half a Hann window. The presentation order of the frequencies and magnitudes was completely randomized.

The method of magnitude estimation was employed to determine intensity judgments. Stimulus pairs, consisting of a reference vibration and test vibration, which had a duration of 1 s each with a 1 s interval between them, were presented. The reference vibration was fixed at 20 Hz with an acceleration level of 110 dB. The task of the subject was to assign a number representing the perceived intensity of the test vibration relative to the intensity of the reference vibration, assuming the intensity of the reference vibration corresponded to 100. If the subjects did not perceive the test stimulus, they were instructed to type 0. These data were removed before further analysis.

The reference and test stimuli were marked visually using the experimental interface controlled by Matlab. Each test participant judged all stimuli three times in one session, lasting approximately 30 min. Before starting the experiment, the subjects were familiarized with the magnitude estimation task by judging the lengths of lines drawn on paper.

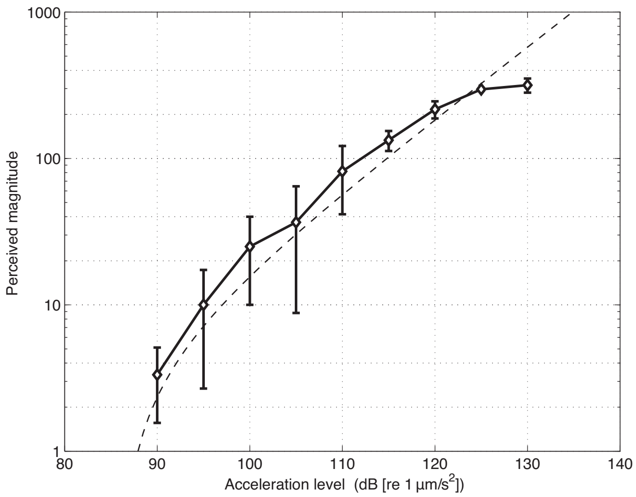

Fig. 5. Example of the growth of sensation for a single test participant and 20 Hz vertical WBVs. Plotted are mean values $\pm$ one standard deviation calculated for the three intra-individual repetitions. The data were fitted using Equation (2). The acceleration level of the reference vibration was 110 dB.

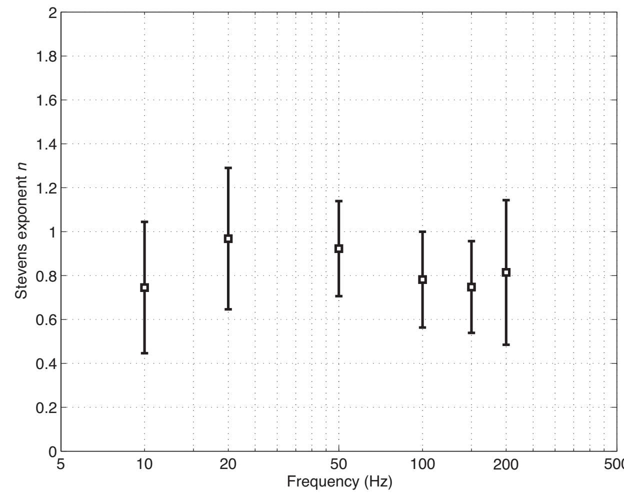

Fig. 6. The rate of growth of sensation expressed as Stevens' exponent as a function of vibration frequency. The means $\pm$ one standard deviation are plotted for 10 subjects. A mean Stevens' exponent of 0.83 was obtained.

V. Results and Discussion

The mean perceived intensities were calculated by averaging the assigned numbers for each subject over the three repetitions. An example is plotted in Fig. 5 for one exemplary subject and a vibration frequency of 20 Hz. A curvilinear relationship was observed for most test participants. For low sensation levels, the data followed Stevens' power law with an additive constant, Eq. (2). However, some deviation at acceleration levels greater than 120 dB were observed. This finding supports the hypothesis that there would be a tendency for subjects to apply a nonlinear scale for mapping stimulus intensities to numbers [22]. The topic has been debated for many decades, and there is still disagreement about the adequate method for measuring suprathreshold sensation magnitude (for a review see Hellbrück and Ellermeier [23]). Stevens' power law with an additive constant was used in this study to fit the individual data to determine the relationship between the sensation magnitude and corresponding acceleration levels. The constant ϕ_0 was taken from a mean perception threshold for vertical seat vibrations. Threshold curves from various laboratories were averaged (for a review see [24]). All individual regressions fit the data well with coefficients of determination, r^2, of 0.9 or greater.

The mean rates of growth of sensation were determined by averaging the individually fitted exponents over all test participants. The resulting Stevens' exponents n are plotted in Fig. 6. Mean values between 0.75 and 0.97 were obtained but with large inter-individual variances. No significant variation with frequency was measured (repeated-measures ANOVA, $p > 5\%$). This finding is supported by other studies, which found little evidence of a frequency dependence of Stevens' exponent for vertical seat vibrations [11], [12], [15].

As discussed earlier, the exponents found in those studies differed depending on numerous factors. For instance, Miwa [11] obtained lower Stevens' exponents compared to the current study using the method of magnitude production. Interestingly, magnitude production typically leads to higher values than magnitude estimation [14]. However, the applied sensation levels were rather high in Miwas study. Thus, the shallower section of the curve was measured, which could explain the lower exponents. In contrast, higher Stevens'

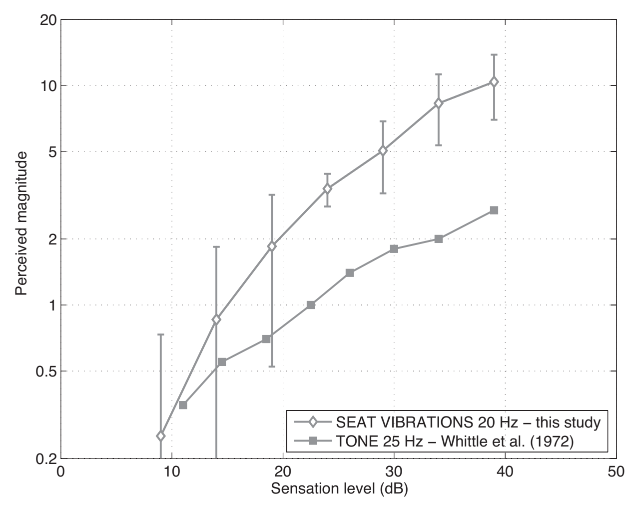

Fig. 7. The growth of perceived magnitude as a function of sensation level for acoustical and vibratory stimuli of approximately 20 Hz. The acoustical stimulus was reproduced using a pressure cabinet, and the method of magnitude estimation was applied [25]. The same method was used to evaluate vertical seat vibrations in this study. Plotted are the mean values averaged over all of the test participants $\pm$ one inter-individual standard deviation. The perceived vibration magnitudes are scaled to fit the loudness data.

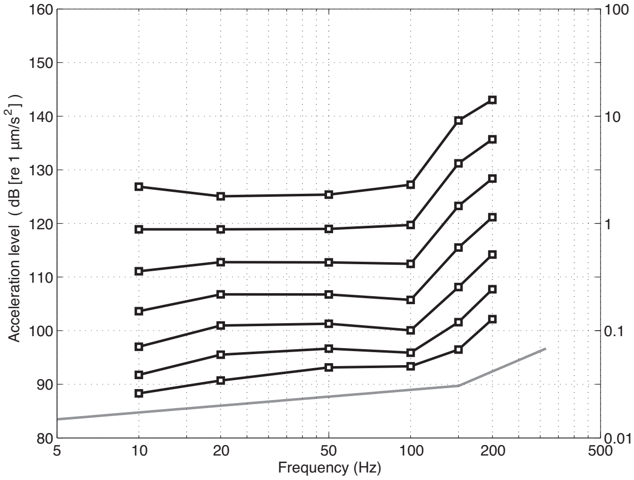

Fig. 8. Contours with equivalent vibration intensity perception of vertical seat vibrations. The contours were calculated from the magnitude estimation data in this study. The distance between two neighboring contours corresponds to a doubling of perceived magnitude. Additionally, the mean perception threshold is plotted [24].

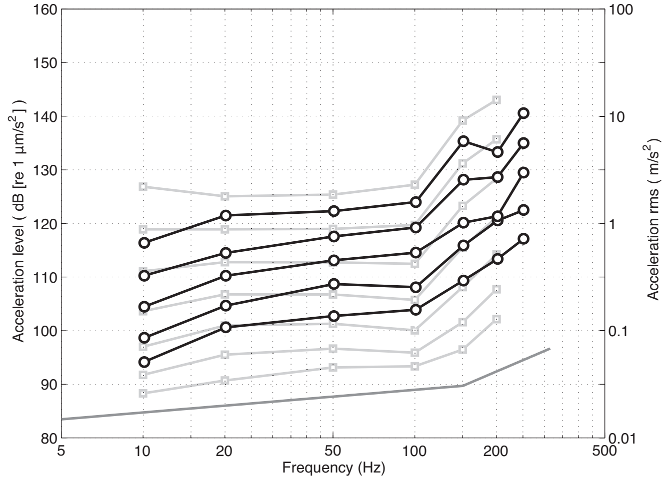

Fig. 9. Comparison of equal intensity contours measured in an earlier study [24] using intensity matching (black) and contours derived from magnitude estimation data in this study (gray). Additionally, the mean perception threshold is plotted.

exponents have been measured by Howarth and Griffin [15], among others. They applied only low acceleration levels and thus measured the steeper section of the curve.

In Fig. 7 the mean perceived intensities obtained in this study at 20 Hz are plotted versus sensation levels between 10 and 40 dB by averaging over all of the test participants. The inter-individual standard deviation was low at a 24 dB sensation level, which corresponds to the reference stimulus at a 110 dB acceleration level.

For comparison, auditory loudness is plotted for a 25 Hz tone in Fig. 7 using data from Whittle et al. [25]. A pressure cabinet was used for sound reproduction, and the method of magnitude estimation was applied. As can be seen, the growth of vibration magnitude is clearly steeper compared to loudness, particularly at low sensation levels. This difference increases toward higher frequencies because Stevens' exponent decreases toward higher frequencies in audition, whereas Stevens' exponent remains constant in the tactile domain.

The magnitude estimation data can also be plotted differently. Equivalent intensity contours can be constructed using the Stevens' exponents shown in Fig. 6. The resulting contours are shown in Fig. 8. The sensitivity to acceleration decreases toward higher frequencies. There is only a gradual decrease in sensitivity as the frequency increases between 10 and 100 Hz, although a more rapid reduction toward higher frequencies is observed. The contours are rather parallel, which visualizes the weak or missing frequency dependence of the growth of vibration magnitude.

The curves of equal vibration intensity can also be measured directly by matching the intensities of various test vibrations to reference vibrations at different levels. This method was applied in a previous study [24]. The results are shown in Fig. 9 for comparison. Good agreement between the datasets can be observed. Both measurements exhibit a pronounced bend at approximately 100 Hz. However, a slightly different increase in acceleration with increasing frequency was observed in the current experiment.

VI. Summary and Outlook

In this study, the growth of perceived intensity was investigated for vertical seat vibrations. The following results were obtained.

- The relationship between sensation intensity and sensation level was determined for seat vibrations using a magnitude estimation method.
- Stevens' exponents between 0.75 and 0.97 were measured. A mean value of 0.83 was obtained.
- No significant variation of Stevens' exponent with frequency was found, indicating that in contrast to audition, tactile suprathreshold intensity perception does not depend on frequency, at least at less than 250 Hz.
- Curves of equal vibration intensity have been determined. Those curves were observed to parallel each other.
- Compared to audition, the increase in perceived magnitude is steeper with increasing level, particularly at low sensation levels.

As discussed above, Stevens exponents determined in different studies have varied. Therefore, more data are necessary for comparison to complete the knowledge. The intensity perception at various body sites should be compared in more detail. Therefore, further experiments are needed, e.g., using vibrations at hand and finger, as well as vibrations for standing, sitting, and lying subjects. Additionally, vertical and horizontal directions should be taken into account.

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