Cross-Modality Matching of Loudness and Perceived Intensity of Whole-Body Vibrations

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Abstract. In this study, two experiments were conducted to determine the point of subjective intensity equality (PSE) of pure tones and sinusoidal whole-body vibrations (WBV) at various frequencies (50 Hz, 100 Hz and 200 Hz). In these experiments, sounds and vertical vibrations were simultaneously presented to subjects using circumaural headphones and a flat hard seat. In total, 10 participants were subjected to tones with a fixed loudness level (40 phon, 60 phon, 80 phon and 100 phon). The participants were asked to match the intensity of the vibration to the loudness of the tone, using the method of adjustment. In the first experiment, the participants were subjected to a vibration and tone with the same frequency. Alternatively, in the second experiment, the frequency of the vibration was maintained at 50 Hz, while that of the tone was varied.

The results revealed that a 20 phon increase in loudness level resulted in a 5-6 dB increase in matched acceleration level at loudness levels greater than 40 phon. This result was reproducible with small intra-individual variations; however, large inter-individual differences were observed.

Keywords: Cross-Modality Matching, Whole-Body Vibration, Audiotactile Perception, Intensity

1 Introduction

By matching different sensory percepts in a virtual environment, a coherent and immersive image can be formed. For instance, vibro-tactile perception can be integrated with other senses (e.g., vision and hearing) to form one multi-modal event.

Previous studies have shown that a synchronous presentation of vertical whole body vibrations during concert reproductions can improve the perceived quality of the concert experience [1, 2]. Since sound and vibration are often coupled in real life, a vibration signal can be generated from an audio recording, for example by low-pass filtering. In the reproduction process, the amplitude of the reproduced vibration must be selected. However, the perceived vibration in a concert hall is often weak and varies with position and frequency, depending on the airborne and structure-borne transmission paths between the source of sound and vibration and the concert visitor. The preferred vibration in a reproduction setting may be different from those in a real environment; thus, a cross-modality matching experiment can be used as a basis for amplitude selection. However, the meaning of the vibration and the user's expectation of concert reproduction cannot be neglected. A similar example is the generation of vibration for action oriented home cinema applications using the audio track [3].

A number of experimental studies have focused on the perception of synchrony between acoustical and vibrational stimuli [4–8]. The subjective equivalence of noise and whole-body vibrations has been investigated, and many studies have focused on the level of participant annoyance. The stimuli used in these studies varies from sinusoidal signals (1000 Hz tone matched with a 10 Hz vibration) [9] to railway noise [10]. The combined effect of noise and vibration on participant performance has also been investigated [11]. Moreover, Kaufmann et al. [12] produced narrow band white noise of vibration (center frequency 31.5 Hz) and sound (center frequency 100 Hz) at three different levels of sound pressure (70 dB, 75 dB, 80 dB). The results of these studies indicated that a 5 dB increase in sound pressure level led to a 2 dB increase in matched acceleration level.

In this study, the point of subjective equality of the intensity of sound and vibration was determined using three sinusoidal stimuli at various loudness levels.

2 Experiments

Two experiments were conducted to determine the point of subjective equality (PSE) for pure tones and sinusoidal whole-body vibrations (WBV). In the first experiment, tones and vibrations with an identical frequency were employed. Alternatively, WBVs and tones with differing frequencies were emitted in the second experiment.

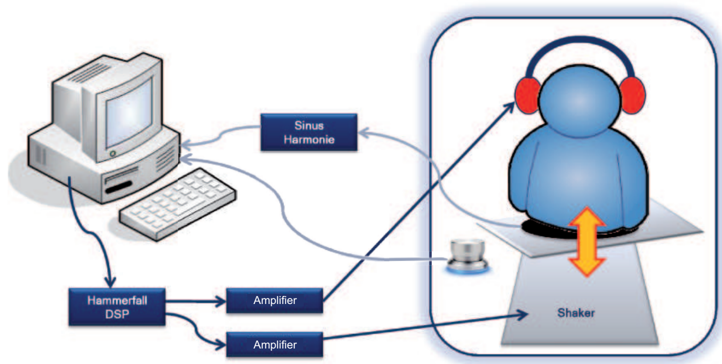

Fig. 1. Experimental setup.

2.1 Setup

Figure 1 shows the general setup used to reproduce sound and vibration. Whole-body vibrations were generated vertically using an electro-dynamic shaker, and the subject was asked to sit on a flat hard wooden seat with both feet on the ground. The transfer characteristic of the vibrating chair is strongly dependent on the individual person [13]. This phenomenon is referred to as the body related transfer function (BRTF). The BRTF of each subject was individually monitored using a vibration pad (B&K Type 4515B) and a Sinus Harmonie quadro measuring board and compensated using inverse filters in Matlab.

The audio signals were delivered through an external Hammerfall DSP Multiface sound card, amplified by a Phone-Amp G93 and reproduced through a set of Sennheiser HDA 200 closed dynamic headphones.

The participant was able to control the amplitude of the vibration using a rotary knob that was infinitely adjustable and did not possess any indicators, such as an on or off mark (Griffin Technology, PowerMate).

2.2 Subjects

10 subjects voluntarily participated in both experiments (8 male and 2 female). Most of the participants were students between 20 and 29 years old (mean 23 years). The participants had masses between 58 and 95 kg (mean 77 kg) and indicated that they did not have any hearing or spinal damage.

2.3 Stimuli and Experimental Design

Three sinusoidal frequencies were selected for this study (50 Hz, 100 Hz and 200 Hz).Tonal and vibrational signals were simultaneously emitted for one second and were faded in and out using half a hanning window of 50 ms flanks. Tones with a fixed loudness level of 40 phon, 60 phon, 80 phon and 100 phon were used as a reference. Figure 2 shows the selected reference tones and corresponding isophones, which were based on ISO 226:2003 [14]. To compare the results to isovibrational contour plots in future studies, isophones were selected as a reference for cross-modality matches.

The task of the participant was to match the amplitude of a vibration to the loudness of a tone. The subjects were able to adaptively adjust the intensity of the vibration using a rotary control knob (with a minimum step size of 0.25 dB). The initial acceleration level of the whole-body vibration was 90 ± 5 dB (a random offset was used for each trial). A low initial acceleration was necessary because the dynamic range of the perception of vibration is small [15], and a high level of vibration may cause discomfort. However, during the training period, subjects

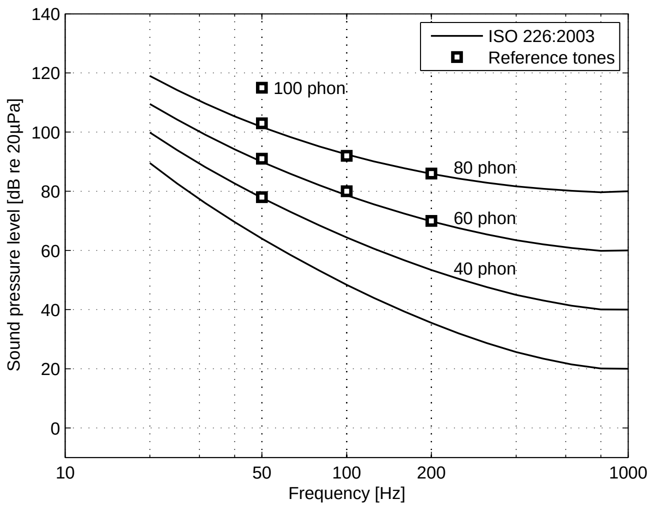

Fig. 2. The reference stimuli were selected to fit loudness contour curves based on ISO 226:2003 [14].

were encouraged to test the entire dynamic range of the reproduction system using the manual amplitude adjustment.

The test stimulus was followed by a one second break, and this sequence was repeated until the subject was satisfied with the intensity match. The subject was free to take as much time as necessary to make the proper adjustment. Each condition was repeated five times for each participant. Before the test began, a five minute training period was conducted to familiarize the participant with the stimuli and test procedure. The total duration of the experiments varied between 20 minutes and 40 minutes, depending on the individual participant.

In the first experiment, the frequency of the tone and vibration was identical. All three frequencies (50 Hz, 100 Hz and 200 Hz) were tested at a loudness of 60 phon and 80 phon. To evaluate the effect of loudness in more detail, additional tones with a loudness of 40 phon and 100 phon, and a frequency of 50 Hz were selected.

Audible harmonics of the vibration frequency are suitable for integrating the two perceptual components [8]. To use this effect for the generation of a vibrational signal from an audio recording, the relationship of cross-modal intensity was investigated for non identical frequencies in the second experiment. In this experiment, the frequency of vibration was fixed at 50 Hz, and the frequency of the tone was varied between 50 Hz, 100 Hz and 200 Hz at a constant loudness level of 60 phon.

3 Results and Discussion

3.1 Experiment 1 - Identical Frequencies

Figure 3 shows the level of acceleration that was matched to the 60 phon (lower curve) and 80 phon (upper curve) tone (averaged over all subjects and repetitions). As expected, the amplitude of the matched vibrations was higher for the 80 phon tone than the 60 phon tone. As shown in Fig. 3, the curves parallel each other at a distance of approximately 6 dB. In addition, the 50 Hz and 100 Hz tone were matched to the same level of acceleration. However, at 200 Hz, the matched acceleration increased by approximately 10 dB. The loudness of the reference tones was equal; thus, these curves may parallel equal-vibration-intensity contour lines. Equal-sensation contour lines are often similar to shifted thresholds. The results from this study can be compared with the threshold for vertical whole-body vibrations, which is flat between 20 Hz and 100 Hz and increases at higher frequencies (for a review see [16]). However, the reported thresholds in previous studies are highly variable, which may be due to large inter-individual deviations [17].

Also in this study, inter-individual differences were much larger than intra-individual deviations. This effect can be readily observed in the results shown in Figure 4, which displays the results of the 60 phon reference tones.

Figure 5 shows the acceleration that was matched to a 50 Hz tone with a loudness of 40 phon, 60 phon, 80 phon and 100 phon. A significant difference was not observed between the matched acceleration of a tone with a loudness of 40 phon and 60 phon. However, at higher loudness levels, the matched acceleration increased by approximately 5 to 6 dB with a 20 phon increase in loudness level. Note that, for a tone with a frequency of 50 Hz, a 20 phon increase in loudness corresponds to a 12 dB increase in sound pressure level (see Figure 2).

3.2 Experiment 2 - Different Frequencies

In the second study, different tones (50 Hz, 100 Hz and 200 Hz) of equal loudness (60 phon) were matched to a single vibration (50 Hz). As expected, the amplitude of the matched vibration was equal under all three conditions, as shown in Figure 6. Thus, the difference between the three conditions was not significant. The absolute value of the matched acceleration was similar to previously reported results. For instance, Kaufmann et al. [12] observed a matched acceleration of approximately 107 dB using narrow band white noise (vibration: center frequency = 31.5 Hz; sound: center frequency = 100 Hz and a sound pressure level of 80 dB, which corresponded to a loudness level of approximately 60 phon). In comparison, the results from this study indicated that an acceleration level of 106 dB matched the 100 Hz reference tone.

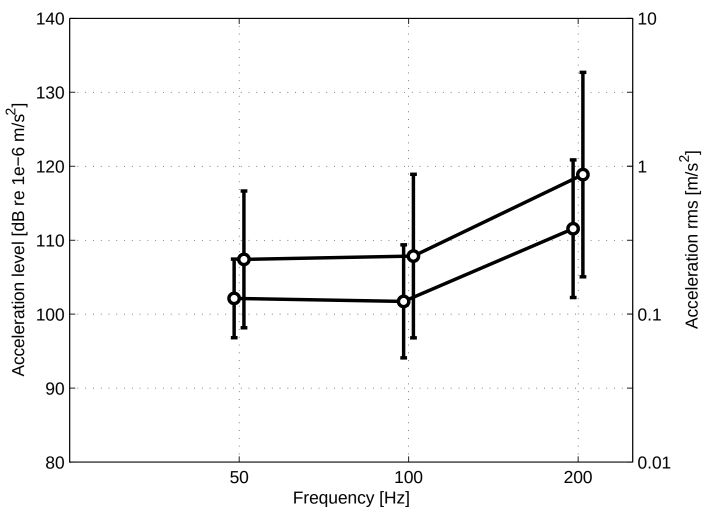

Fig. 3. Mean ± the standard deviation of the inter-individual results of cross-modality matching studies based on reference tones with a loudness of 60 phon (lower curve) and 80 phon (upper curve). To clearly illustrate the results, the frequency of each data point was shifted slightly.

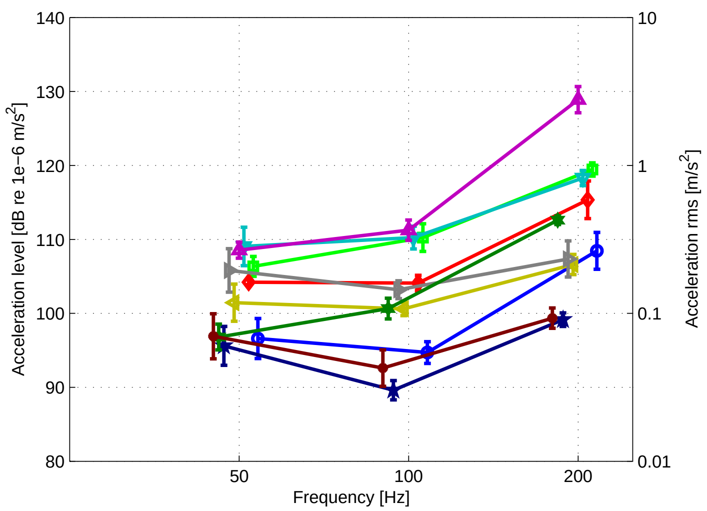

Fig. 4. Mean ± the standard deviation of intra-individual results of cross-modality matching studies based on reference tones with a loudness of 60 phon. To clearly illustrate the results, the frequency of each data point was shifted slightly.

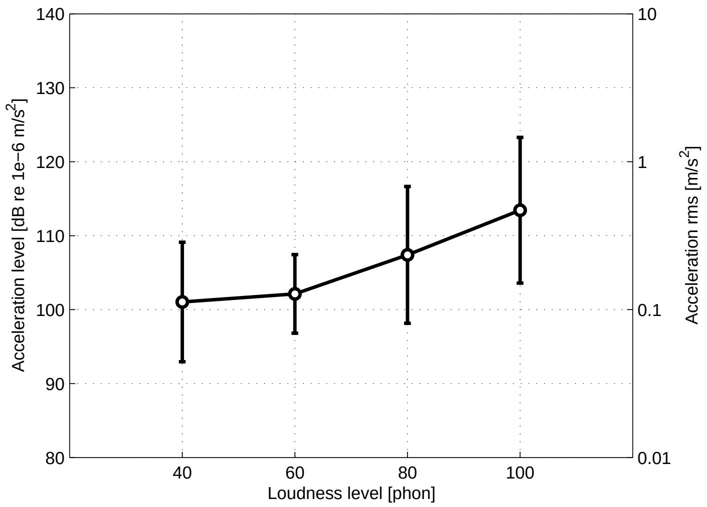

Fig. 5. Mean and standard deviation of the results of cross-modality matching with a 50 Hz vibration and a 50 Hz reference tone at a loudness level of 40 phon, 60 phon, 80 phon and 100 phon. Note that at 50 Hz, a 20 phon increase in loudness level does not correspond to 20 dB increase in acceleration level (see Figure 2).

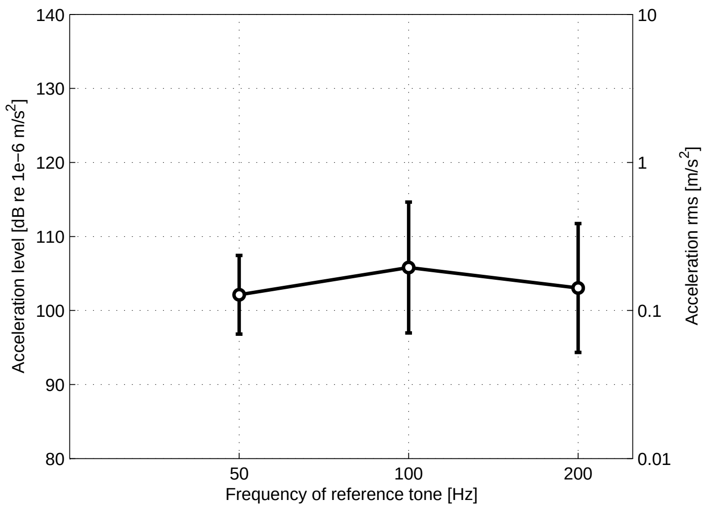

Fig. 6. Mean and standard deviations of the results of cross-modality matching studies for a 50 Hz vibration and reference tones at 50 Hz, 100 Hz and 200 Hz with a loudness level of 60 phon.

The method of adjustment used in this study was fast and reliable. However, the beginning acceleration values were consistently lower than the matched values; thus, the results may slightly underestimate the PSE of intensity.

4 Summary and Outlook

In this study, points of subjective equality for the loudness of pure tones and the perceived intensity of sinusoidal whole-body vibrations were determined, and the following results were obtained:

- The matched acceleration level of a tone with a specific loudness (60 phon or 80 phon) was similar at 50 Hz and 100 Hz; however, the matched acceleration increased significantly at 200 Hz.
- A 20 phon increase in loudness level resulted in a 5-6 dB increase in matched acceleration level.
- Small intra-individual and large inter-individual variations were observed.
- For a 50 Hz whole body vibration, tones of equal loudness were matched to the same acceleration level, even if the acoustic frequencies were different from the frequency of vibration.

The results of this study will be compared with equal-vibration-sensation contour plots, which are investigated at the moment. Moreover, in a subsequent study, the frequency range or resolution could be expanded, or natural (broad band) signals could be employed.

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