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Just-Noticeable Frequency Differences for Whole-Body Vibrations

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ABSTRACT

In this study, an experiment was conducted to determine frequency discrimination for sinusoidal vertical whole-body vibrations (WBV) with frequencies between 20 Hz and 90 Hz in an adaptive, two-interval, forced-choice psychophysical procedure. The vibrations were reproduced using an electrodynamic shaker and a flat, hard and wooden seat. The stimuli had a length of 1 s, and their amplitudes were carefully normalized to achieve a uniformly perceived magnitude (approximately 20 dB above threshold). To acoustically mask the sound emitted by the vibration system, pink noise was presented over a set of headphones at 74 dB(A). The perceivable frequency differences increased with increasing frequency. The Weber fraction was relatively large (between approximately 35% and 80%). Small intra-individual and large inter-individual differences were observed at higher frequencies.
Keywords: just-noticeable frequency differences, whole-body vibration, tactile perception.

1. INTRODUCTION

The minimum detectable change in frequency of a sinusoid is a fundamental characteristic of the tactile sense. This must be considered, for example, when evaluating and modifying the vibration characteristics of vehicles. Few studies have explored the difference limen of tactile frequency discrimination. Only one study, by Bellmann [1], is known, which addressed whole-body vibrations (WBV) using an adaptive, three-alternative, forced-choice method. Six subjects participated in the experiment. Four reference frequencies (5 Hz, 10 Hz, 20 Hz and 40 Hz) with a fixed acceleration level of L_{acc} = 96 dB re 1×10^{-6} m/s² have been tested. Bellmann found a linear increase in the just-noticeable difference in frequency (JNDF) with increasing frequency. The difference limen (JNDF) ranged from approximately 0.4 Hz (for 5 Hz) to 12 Hz (for 40 Hz), corresponding to Weber fractions (JNDF / f_{ref}) of 8% to 30%, respectively. There have been no studies on whole-body vibrations above 40 Hz.

Other studies have focused on the vibrotactile stimulation of the hand and forearm. Goff [2] investigated sinusoidal stimulation at the fingertip. A two-stimulus forced-choice procedure was used. Four subjects participated in the experiment. Five reference frequencies (25 Hz, 50 Hz, 100 Hz, 150 Hz and 200 Hz) were selected, and their magnitudes were adjusted to equal intensities (approximately 20 dB above the threshold). He found that the difference limen (JNDF) ranged from 5 Hz to over 100 Hz, increasing with increasing reference frequency. This corresponds to Weber fractions (JNDF / f_{ref}) of 20% to 55%, respectively.

Rothenberg et al. [3] experimented with sinusoidal stimuli at the volar forearm. A two-stimulus forced-choice procedure was used. Five subjects participated in the experiment. Reference frequencies between 25 Hz and 250 Hz were evaluated. Their amplitudes were normalized to achieve a uniform subjective magnitude (14 dB above threshold). The results revealed a difference limen (JNDF) ranging from 4 Hz to over 75 Hz, which corresponds to Weber fractions (JNDF / f_{ref}) of 16% to 30%, respectively.

The ability to detect changes in vibration frequency at the thenar eminence was measured by LaMotte and Mountcastle [4] using 30 Hz sinusoids. They found a JNDF of 1.8 Hz, which corresponds to a Weber fraction (JNDF / f_{ref}) of 6%. This high sensitivity might be explained by the considerable training of the participants.

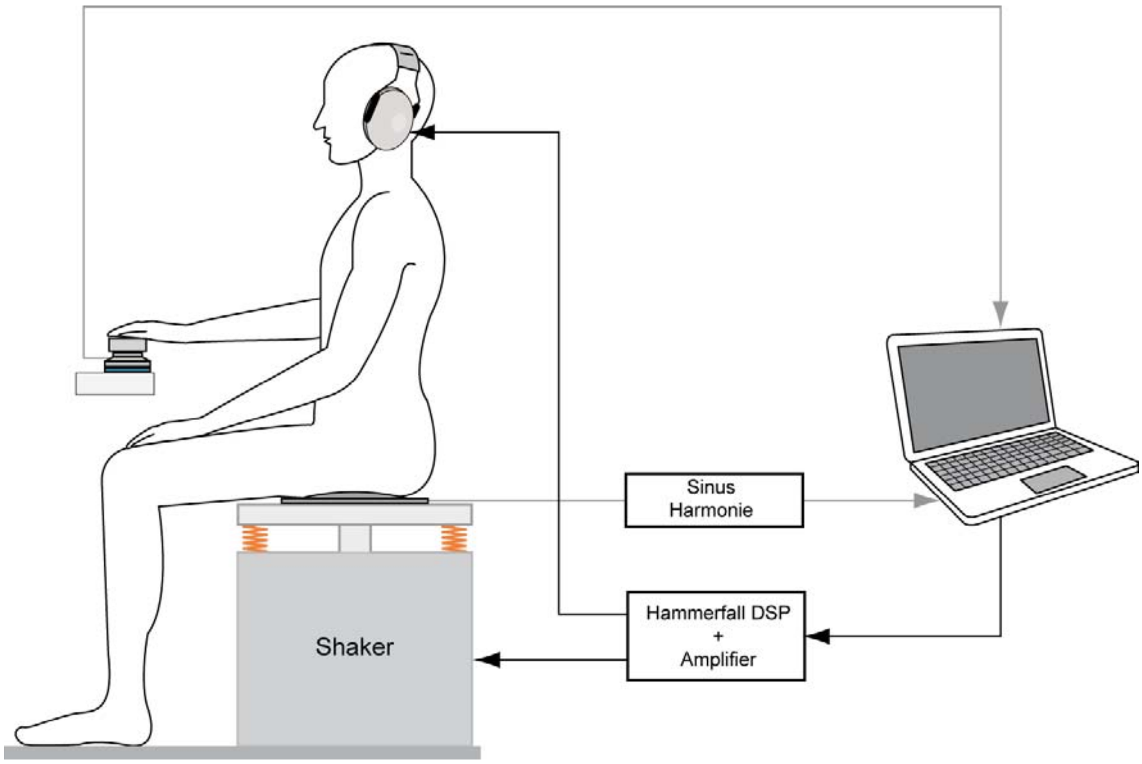

Figure 1 – Experimental setup.

2. EXPERIMENT

2.1 Setup

The setup used to produce sound and vibration is shown in Figure 1. Vertical whole-body vibrations were generated using an electrodynamic shaker. The subjects were seated on a flat, hard and wooden seat with both feet on the ground. The transfer characteristics of the vibrating chair strongly depend on the individual person [5]. This phenomenon is called 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. Inverse filters in MATLAB were used to compensate for each BRTF.

At higher frequencies, the vibration chair can emit acoustic noise. To mask these signals, pink noise, presented at 74 dB(A), was delivered through an external Hammerfall DSP Multiface II sound card, amplified by a Phone-Amp G93 and reproduced through a set of Sennheiser HDA 200 closed dynamic headphones.

2.2 Subjects

Fifteen subjects (9 male and 6 female) voluntarily participated in the experiment. Most of the participants were students and were between 19 and 27 years old (mean, 23 years old). The participants' weights ranged from 62 to 85 kg (mean, 71 kg). They indicated that they had no hearing impairment or spinal damage.

2.3 Stimuli and Experimental Design

To accurately measure the differential frequency thresholds of a cutaneous mechanical vibratory stimulus, concomitant changes in the subjective intensity should be eliminated. Therefore, equal-vibration perception curves were measured for whole-body vibrations in a previous experiment [6]. Using these data, the stimulus amplitudes in this experiment were carefully normalized to achieve a uniformly perceived magnitude (approximately 20 dB above threshold).

In a preliminary experiment, it was found that, above 90 Hz, the perceived location of the vibration started to move along the thigh, depending on various factors, such as clothing and posture. These localization cues for stimulus discrimination complicated the measurements of the differential frequency thresholds. Thus, reference frequencies (f_{ref}) between 20 Hz and 90 Hz at 10 Hz intervals were chosen.

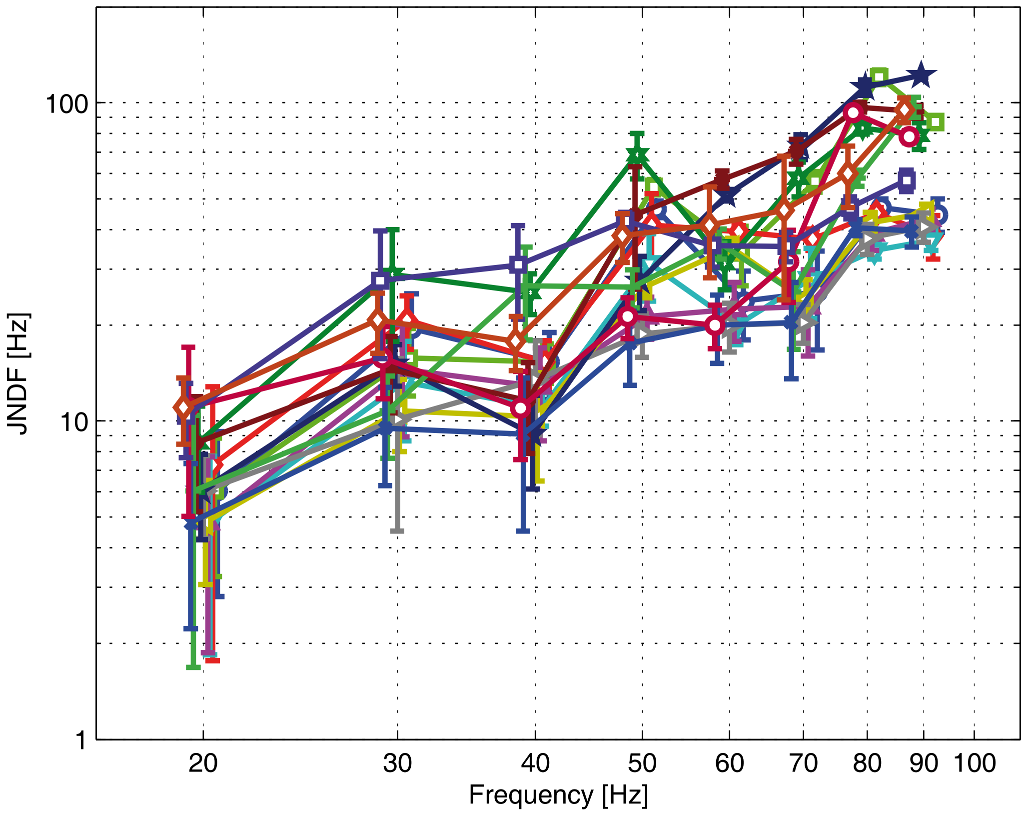

Figure 2 – Mean of the individual difference threshold ± intra-individual standard deviation for all 15 subjects. To better illustrate the results, the frequency of each data point was shifted slightly.

An adaptive, two-interval, forced-choice, 1-up/1-down psychophysical procedure was used. The subjects were presented with two consecutive randomized stimuli and were asked to decide whether the frequencies were identical. Both stimuli had a length of 1 s, with a 0.5 s break between them. The test stimulus started at a frequency (f_{test}) of 80 Hz above the frequency of the reference stimulus (f_{ref}). Thus, this experiment only measured positive JNDFs ($f_{test} > f_{ref}$). The initial step size of 20 Hz was halved after each upper reversal (up → down) to a final step size of 2.5 Hz. After the final step size was reached, the measurement phase started. The individual difference threshold was obtained by calculating the mean of the values during the measurement phase, which was terminated after five upper reversals. The entire experiment lasted approximately 30-40 minutes per participant, including an initial familiarization phase.

3. RESULTS AND DISCUSSION

The measured individual difference limens in frequency are plotted in Figure 2 as mean values and their intra-individual standard deviations. The intra-individual standard deviations remained almost constant, whereas the inter-individual variations increased with increasing frequency (e.g., approximately 2 Hz at f_{ref} = 20 Hz and 27 Hz at f_{ref} = 90 Hz). Note that the plot has a double-logarithmic scale.

Figure 3 shows the data averaged across all of the subjects with the corresponding inter-individual standard deviations. The mean JNDF increased with frequency, from approximately 7 Hz at f_{ref} = 20 Hz to 66 Hz at f_{ref} = 90 Hz. The Pearson product-moment correlation between the logarithmized JNDFs and the logarithmized reference frequency was statistically significant, with $r^2 = 0.94$ ($p<0.01$). Therefore, a linear regression curve was calculated using a least-squares approach in the double-logarithmic domain. This corresponds to a power function in the linear domain: $JNDF = 0.1 \cdot f_{ref}^{1.44}$. The regression curve and the averaged data are plotted in Figure 3. The JNDF increases from approximately 7 Hz at 20 Hz to 65 Hz at 90 Hz.

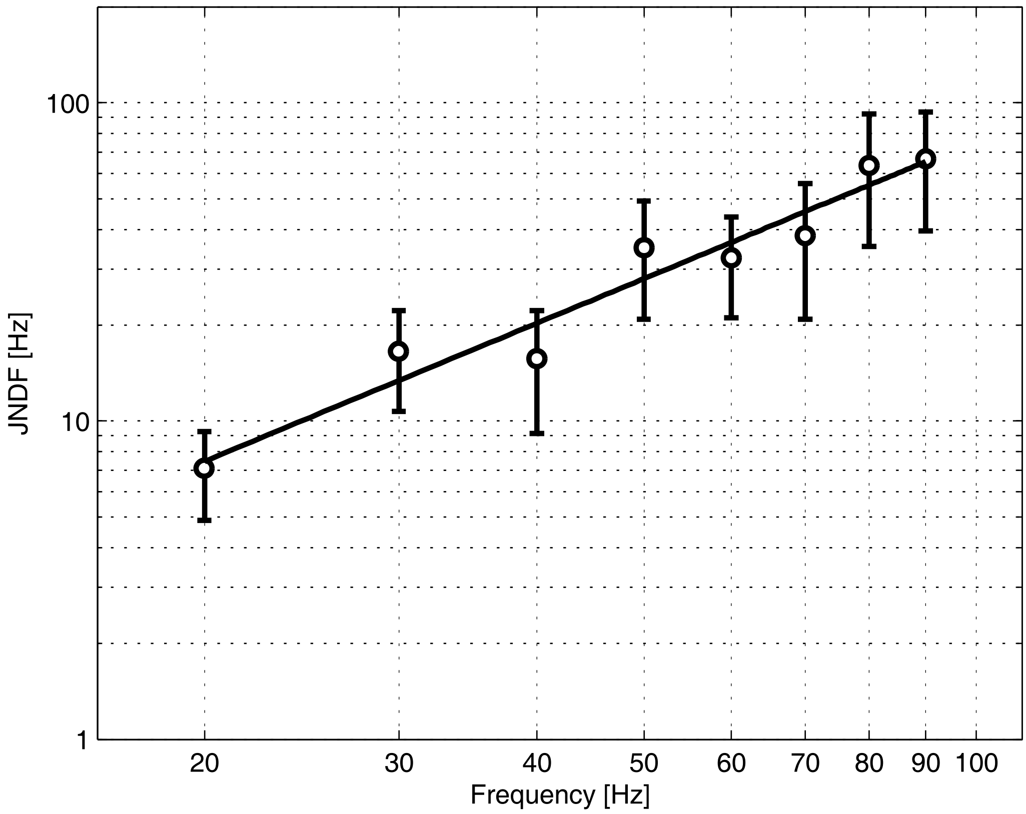

Figure 3 – Averaged frequency difference thresholds ± inter-individual standard deviations for all 15 subjects. Additionally, a first-order regression line was fitted to the data.

Because the difference limen tends to directly vary with frequency, it is common to plot the results as Weber fractions (JNDF / f_{ref}). Weber found that the perceivable difference in the stimulus intensity is a constant fraction of the reference intensity for medium-intensity stimuli [7]. The solid line in Figure 4 represents the data plotted in Figure 3. The Weber fraction increases from approximately 35% to 80% at higher frequencies. The values at 20 Hz and 40 Hz are comparable to the whole-body vibration results determined by Bellmann, who used a similar psychophysical procedure [1]. However, his values are considerably smaller at lower frequencies. In his study, improved discrimination could, at least partially, be explained by the absence of compensation for concomitant changes in the subjective intensity.

When comparing the results of this study to the frequency difference limens reported in literature for various locations on the arm and hand, inferior frequency discrimination is found. This could be partially explained by the fact that only positive JNDFs ($f_{test} > f_{ref}$) were measured in this study. Customarily, the frequency difference threshold is considered to be one-half of the difference limen for positive and negative JNDFs. Another possible reason for the superior discrimination results in the literature might be the higher tactile sensitivity of the hand and/or forearm. Interestingly, the frequency discrimination observed by Rothenberg et al. at the forearm [3] was better than the frequency discrimination observed by Goff at the more sensitive finger [2]. The even more superior result by LaMotte et al. at 30 Hz [4] could have been due to the use of highly trained subjects. Other studies that used pulse trains or warble tones will not be discussed here.

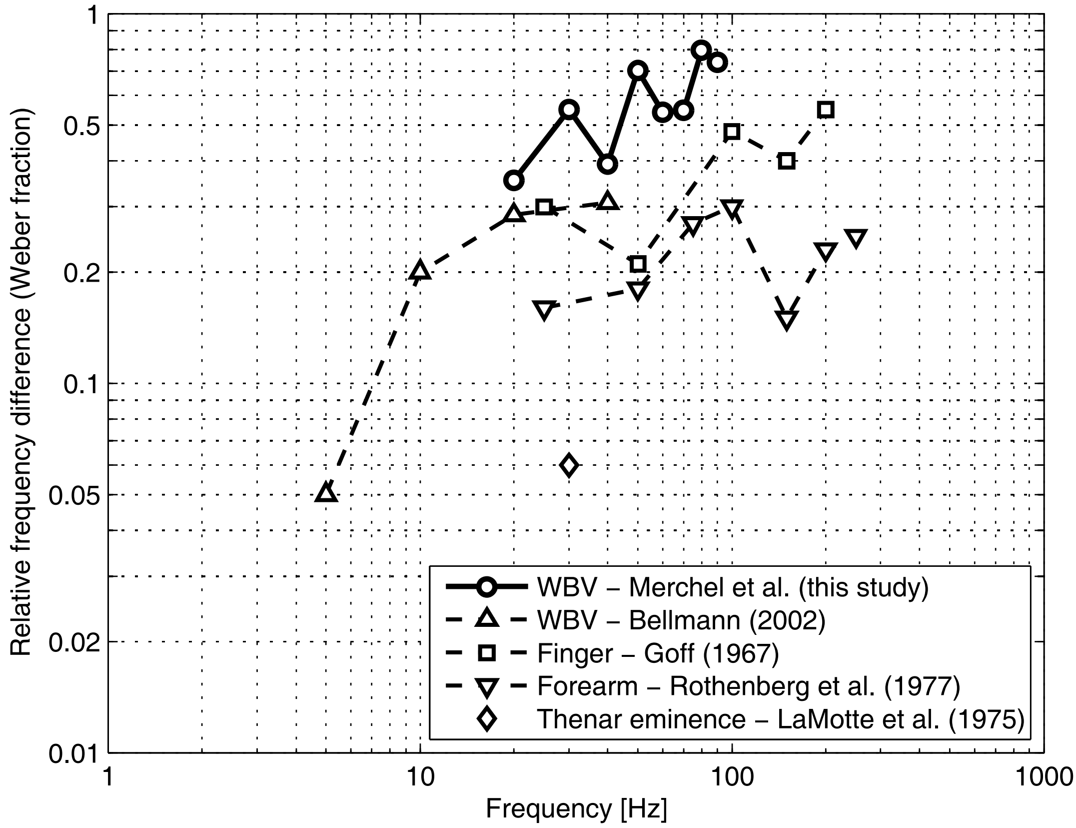

Figure 4 – The relative frequency difference (JNDF / f_{ref}; Weber fraction for frequency) for sinusoidal vibrations at various body sites is shown as a function of the reference frequency. The dashed lines and the diamond indicate results from other laboratories.

4. SUMMARY AND OUTLOOK

In this study, the ability to discriminate among various vertical, sinusoidal, whole-body vibration frequencies was investigated. Just-noticeable differences in frequency (JNDFs) were measured while carefully eliminating any concomitant changes in the subjective intensity or stimulation location. The results may be summarized as follows:

- The JNDF increases with frequency, from approximately 7 Hz at f_{ref} = 20 Hz to 66 Hz at f_{ref} = 90 Hz.

- This corresponds to Weber fractions (JNDF / f_{ref}) between approximately 35% and 80%.

- Positive JNDFs were measured ($f_{test} > f_{ref}$), which may underestimate the ability to discriminate WBV frequencies.

If the present results are compared to audition, much lower JNDFs are found. In a broad frequency range, Weber fractions below 1% are common for auditory frequency discrimination [8].

It is known from audition that the threshold required to discriminate between two slightly different frequencies depends, to some degree, on the stimulus level. Increased sound pressure levels result in lower JNDFs [8]. In a subsequent study, the dynamic ranges of the sinusoidal whole-body vibrations could be varied. In addition, negative JNDFs ($f_{test} < f_{ref}$) should be measured.

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