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Difference thresholds for vibration of the foot: Dependence on frequency and magnitude of vibration

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ABSTRACT

The smallest change in vibration intensity for the change to be perceptible (i.e. intensity difference threshold) has not previously been reported for vibration of the foot. This study investigated the influence of vibration magnitude and vibration frequency on intensity difference thresholds for the perception of vertical sinusoidal vibration of the foot. It was hypothesised that relative intensity difference thresholds (i.e. Weber fractions) for 16-Hz vibration mediated by the non-Pacinian I (NPI) channel would differ from relative intensity difference thresholds for 125-Hz vibration mediated by the Pacinian (P) channel. Absolute thresholds, difference thresholds, and the locations of vibration sensation caused by vertical vibration of the right foot were determined for 12 subjects using the up-down-transformed-response method together with the three-down-one-up rule. The difference thresholds and locations of sensation were obtained at six reference magnitudes (at 6, 9, 12, 18, 24, 30 dB above absolute threshold—i.e. sensation levels, SL). For 16-Hz vibration, the median relative difference thresholds were not significantly dependent on vibration magnitude and were in the range 0.19 (at 30 dB SL) to 0.27 (at 9 dB SL). For 125-Hz vibration, the median relative difference thresholds varied between 0.17 (at 9 dB SL) and 0.34 (at 30 dB SL), with difference thresholds from 6 to 12 dB SL significantly less than those from 18 to 30 dB SL. At vibration magnitudes slightly in excess of absolute thresholds (i.e. 6–12 dB SL) there were no significant differences between Weber fractions obtained from the P channel (at 125 Hz) and the NPI channel (at 16 Hz). At 24 and 30 dB SL, the 125-Hz Weber fractions were significantly greater than the 16-Hz Weber fractions. Differences in the 125-Hz Weber fractions may have been caused by a reduction in the discriminability of the P channel at high levels of excitation, resulting in one or more NP channel mediating the difference thresholds at magnitudes greater than 18 dB SL. At high magnitudes, a change of channel mediating the Weber fractions may have been responsible for different Weber fractions with 16- and 125-Hz vibration.

1. Introduction

A difference threshold, also called a 'differential threshold', 'difference limen', or 'just noticeable difference', is defined as 'the difference in value of two stimuli that is just sufficient for their difference to be detected' [1]. Difference thresholds can be expressed as either the 'absolute change' in the stimulus required to detect the change, or as the 'proportional change' in the stimulus required to detect the change, called 'relative difference threshold' or 'Weber fraction' (after psychophysicist E.H. Weber). Weber proposed that, for a particular sensation, difference thresholds for the detection of changes in the

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intensity of a stimulus are constant:

$$\frac{\Delta I}{I} = \text{constant} \tag{1}$$

where I denotes stimulus intensity and ΔI is the absolute difference threshold [2].

Difference thresholds for the perception of vibration can assist the optimisation of comfort in transport, since they indicate how much a vibration needs to be reduced for an improvement to be detected by a test driver or noticed by a passenger. It may be assumed that a single change in vibration intensity less than the difference threshold will not alter a passenger's assessment of ride comfort.

Four 'channels' appear to be involved in the perception of vibration applied to the glabrous skin, with the absolute threshold for vibration perception being mediated by different channels at different frequencies [3,4]. Studies of the perception of vibration at the thenar eminence on the hand suggest that absolute thresholds for the perception of vibration at frequencies less than about 2 Hz are likely to be mediated by the 'non-Pacinian III channel'. At frequencies between about 2 and 40 Hz, the 'non-Pacinian I channel' probably mediates absolute thresholds. At frequencies greater than about 40 Hz, absolute thresholds are mediated by the 'Pacinian channel', which has sensitivity to displacement of the skin that increases with increasing frequency up to about 250 Hz and then declines. The fourth channel, 'non-Pacinian II channel', has greatest sensitivity to displacement in a frequency range similar to the P channel, but with a sensitivity less than the P channel in most contact conditions. While the channels responsible for absolute thresholds have been suggested, the mechanisms responsible for the perception of changes in magnitude at supra-threshold levels, and whether the difference threshold depends on the channel mediating the sensation of vibration, is less clear.

For the hand, some studies have found that relative difference thresholds depend on the magnitude of vibration, contrary to Weber's Law. With 25- and 250-Hz sinusoidal vibration applied by a 2.9 cm^2 contactor to the thenar eminence of the hand, Gescheider et al. [5] found reductions in Weber fractions with increasing vibration magnitude: from 0.26 at 4 dB SL to 0.12 at 40 dB SL (where SL is the sensation level—the level of the vibration stimulus expressed in decibels (dB) relative to the subject's absolute threshold expressed in decibels). The Weber fractions were similar at the two frequencies (differing by less than about 0.05). With 250-Hz sinusoidal vibration, and similar contact conditions, Gescheider et al. [6] found that Weber fractions decreased from 0.26 at 4 dB SL to 0.16 at 36 dB SL. Again with 250-Hz vibration and similar contact conditions, Gescheider et al. [7] also found reductions in Weber fractions with increasing vibration magnitude. Gescheider et al. [5] suggested the reduction could be due to a spread of the vibration excitation at higher magnitudes. However, Gescheider et al. [7] suggested that reductions in Weber fractions may have resulted from the involvement of channels other than the P channel at higher magnitudes, particularly the involvement of the NPII channel. In contrast to the Gescheider studies, with the whole hand gripping a handle vibrating at 125 Hz, Forta [8] found that Weber fractions were greater at higher magnitudes (in the range 18–36 dB SL) than at a lower magnitude (12 dB SL).

Few studies have investigated foot-transmitted vibration, and there are no known studies of difference thresholds for the perception of vibration applied to the foot. Equivalent comfort contours showing how the perception of vibration of the whole foot depends on the frequency of vibration at supra-threshold levels have been reported by Parsons et al. [9], Rao [10], Miwa [11] and Morioka and Griffin [12]. Thresholds at specific locations on the foot have also been reported, usually in the context of the detection of sensorineuropathy (e.g., Refs. [13–15]). Absolute thresholds for vibration of the entire foot have been reported by Morioka and Griffin [16] using 12 subjects and vibration stimuli and contact conditions similar to those in the current experiment. They used sinusoidal vibration and determined absolute thresholds over the frequency range from 8 to 315 Hz. The absolute thresholds for vertical vibration (expressed in terms of acceleration) were independent of frequency from 8 to 25 Hz, but dependent on frequency at higher frequencies, defining a U-shaped contour with the lowest threshold at about 100 Hz, and greatly increased threshold at 200 and 315 Hz. The median thresholds were 0.040 m s^{-2} rms at 16 Hz and 0.029 m s^{-2} rms at 125 Hz.

The experiment presented here was designed to investigate the influence of vibration magnitude and vibration frequency on intensity difference thresholds for vertical sinusoidal vibration of the entire foot at 16 and 125 Hz. These two frequencies were chosen to assist the identification of the channels involved in the perception of vibration. To avoid complications arising from differences between the two feet, difference thresholds were determined for only one foot. At vibration magnitudes less than 12 dB SL it was expected that vibration at 16 and 125 Hz would primarily excite the non-Pacinian I (NPI) and the Pacinian (P) channels, respectively. At these low levels of vibration it was hypothesised that relative intensity difference thresholds for 16-Hz vibration mediated by the NPI channel would differ from those for 125-Hz vibration mediated by the P channel. With both frequencies of vibration, it was expected that relative intensity difference thresholds would change when the vibration magnitude increased above 12 dB SL, as the vibration became sufficient to excite other channels according to the four-channel model of vibrotactile perception [3,4].

2. Method

2.1. Apparatus

Vibration stimuli were generated and measured using *HVLab* software (version 3.81) running in a personal computer. Signals were generated at 5000 samples per second and passed through a 300-Hz low-pass filter to an MB Dynamics Model

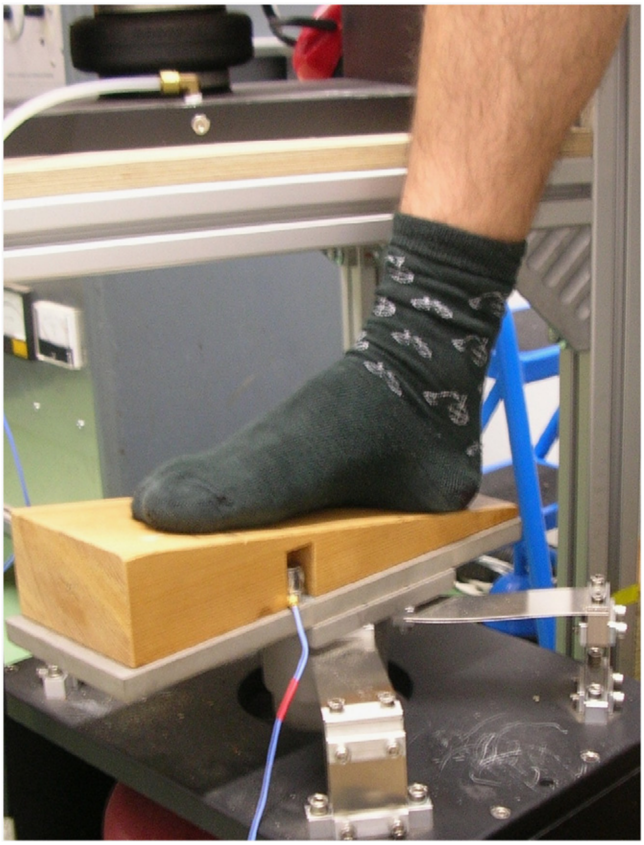

Fig. 1. Experimental set-up and posture.

SL 500VCF power amplifier connected to a MB Dynamics electro-dynamic vibrator. The vibrator applied vertical sinusoidal vibration to the right foot via a rigid wooden platform inclined by 10 degrees, with the rear lower than the front so as to maintain subject comfort (Fig. 1). Vibration was measured using a piezo-electric accelerometer (D.J. Birchall, model A/20T) attached to the footrest. The vibration acceleration signal was acquired via a Techfilter anti-aliasing filter (1000 Hz low-pass) to a PCL-818 12-bit analogue-to-digital converter.

Subjects sat with an upright posture on a stationary seat with no backrest and with their feet on the two identical footrests described above. Only the right foot was exposed to vibration.

2.2. Procedure

The experiment was conducted in two sessions on different days, each lasting about 75 minutes. Prior to commencing the experiment, subjects removed their shoes (but not their socks) and rolled their trousers up above the knee so as to remove any cues due to the trousers moving relative to the skin (Fig. 1).

A session involved either 16 or 125 Hz vibration and consisted of two measures of the absolute threshold and six measures of the difference threshold (at 'reference magnitudes' 6, 9, 12, 18, 24, and 30 dB above the subjects' absolute threshold). Additionally, subjects were exposed to the six reference vibration magnitudes separately and asked to report the location where they experienced maximum sensation. All vibration stimuli had total durations of 2 s, including 0.5-second rise and decay times.

Both sessions commenced with the measurement of the absolute threshold, used to calculate the six 'reference magnitudes' for the difference threshold tests. The locations at which the maximum sensation was experienced when exposed to the reference magnitudes were then determined using a diagrammatic representation of the foot and lower leg (Fig. 2). After one practice measurement, difference thresholds were then determined at the six reference magnitudes in a Latin square balanced order. After each determination of a difference threshold, subjects were asked to identify the body location where they detected the difference between the two vibration stimuli (Fig. 2). At the end of each session, the absolute threshold was measured again.

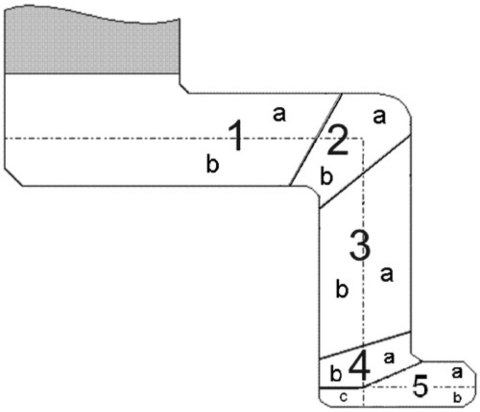

Fig. 2. Diagrammatic representation of the foot and the lower leg used to determine the locations of vibration sensations and differences in vibration magnitude.

Auditory masking (white noise at 75 dBA) was presented via headphones. The skin temperature of the right foot was measured with a thermocouple at the sole of the foot before and after the measurements, because absolute thresholds are dependent on temperature, especially in the Pacinian channel [17].

2.3. Subjects

Twelve healthy male subjects aged between 20 and 28 years (mean age 24.1 years, mean stature 177.8 cm, mean weight 72.5 kg) took part in the experiment. All subjects were either members of staff or students at the University of Southampton. The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

2.4. Psychophysical method

The up-down-transformed-response, UDTR, method was used to determine both the absolute thresholds and the difference thresholds [18]. In the UDTR method, the magnitude of the test stimulus is increased or decreased according to the response of the subject. The stimuli were presented with a two-interval forced-choice procedure and the responses of the subject were tracked using a three-down-one-up rule: if the subject gave three consecutive correct responses, the level of the next test stimulus was reduced by one step, if the subject gave an incorrect response, the level of the next test stimulus was increased by one step. A red light was used to indicate the duration of the two intervals.

To determine a difference threshold, one presentation interval contained the test stimulus and another contained the reference stimulus. The order of the test stimulus and the reference stimulus was randomly determined for each trial. The 2-second reference vibration and the 2-second test vibration were separated by a 1-second pause. The test vibration was always at a greater level than the reference vibration. The magnitude of the test stimulus was modified in accord with the three-down-one-up rule, with a step size of 0.25 dB. The subjects were asked to identify the interval that contained the stronger stimulus. At the first trial, all subjects were presented with a test stimulus at a level where they were able to detect the difference between the two stimuli.

The absolute thresholds were determined with a similar procedure. One of the two intervals contained the test stimulus while the other interval contained no stimulus. The subjects' task was to determine the interval that contained the test stimulus. The magnitude of the test stimulus was modified according to the three-down-one-up rule, with a step size of 3 dB. At the first trial, all subjects started at a level where they were able to detect the test stimulus.

The absolute thresholds and the difference thresholds were calculated from reversal points (i.e. trials at which the direction of the change of stimulus magnitude was reversed). Trials were terminated after six reversals. The thresholds were calculated from the average of the final four reversals, ignoring the first two reversals.

An absolute difference threshold was calculated using

$$\text{Absolute difference threshold} = \sum_{i=3}^{N=6} \left(\frac{M_i - R_i}{(N-2)} \right) \tag{2}$$

where N is the number of reversals (N=6), M_i and R_i are, respectively, the measured rms acceleration magnitude of the test vibration and the measured rms acceleration magnitude of the reference vibration at a reversal. Eq. (2) was also used for calculating the absolute threshold, with the R_i equalling zero.

To determine a Weber fraction, the absolute value of the difference threshold for that stimulus was divided by the rms acceleration magnitude of the reference vibration, R_i:

$$\text{Weber fraction} = \sum_{i=3}^{N=6} \left(\frac{M_i - R_i}{R_i(N-2)} \right) \tag{3}$$

2.5. Statistical methods

Mathworks Inc. MATLAB (R14) software with Statistics Toolbox, was used to calculate the thresholds and perform the subsequent statistical analysis of the results. Non-parametric tests (Friedman and Wilcoxon matched-pairs signed ranks for two-related samples) were employed in the statistical analysis without adjustment for multiple comparisons. Cochran's Q and McNemar tests were employed to investigate the location at which vibration was perceived. These tests were conducted using SPSS Inc. SPSS 16.0 software.

3. Results

All subjects had foot temperatures greater than 25 °C, except for one subject with a foot temperature of 23 °C.

3.1. Absolute thresholds

Absolute thresholds for 16-Hz vibration were significantly greater than those for 125 Hz vibration at both the beginning and the end of the session (Wilcoxon, p=0.0005). The median threshold for 16-Hz vibration rose by 21% (i.e. 1.7 dB), from 0.034 m s^{-2} rms at the beginning of the session to 0.042 m s^{-2} rms at the end of the session (Wilcoxon, p=0.0068, Fig. 3). The median threshold for 125-Hz vibration rose by 30% (2.28 dB), from 0.014 m s^{-2} rms at the beginning of the session to 0.018 m s^{-2} rms at the end of the session, but the difference was not statistically significant (Wilcoxon, p=0.1099, Fig. 3).

3.2. Difference thresholds

As the reference level increased from 6 to 30 dB SL, the median absolute difference thresholds increased from 0.016 to 0.205 ms^{-2} rms at 16 Hz and from 0.007 to 0.150 m s^{-2} rms at 125 Hz (Fig. 4). With 16-Hz vibration, the absolute difference thresholds increased less than predicted by Weber's Law: as the reference magnitude increased by a factor of 16 the difference threshold increased by a factor of 12.5. With 125-Hz vibration, the absolute difference thresholds increased

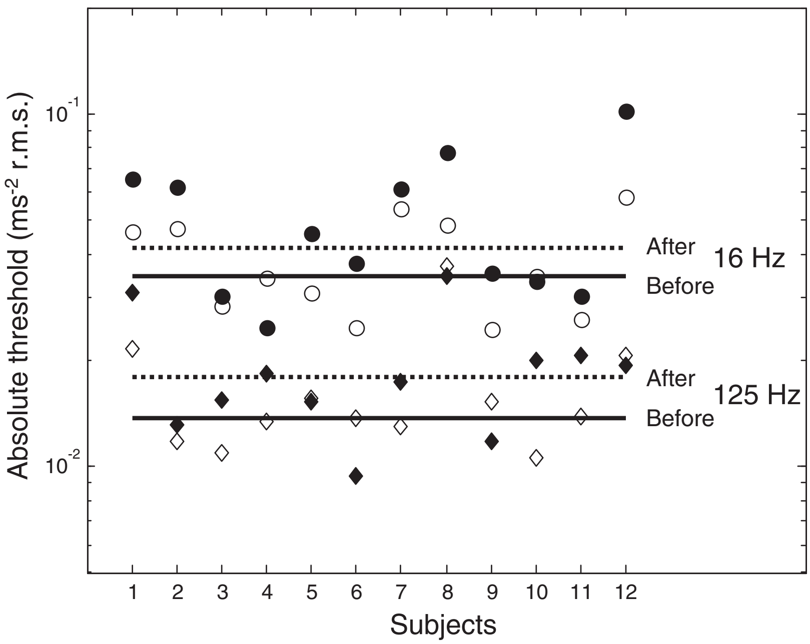

Fig. 3. Absolute thresholds for vertical vibration at 16 and 125 Hz. Thresholds were measured twice for each subject at each frequency, once before and once after the determination of difference thresholds.

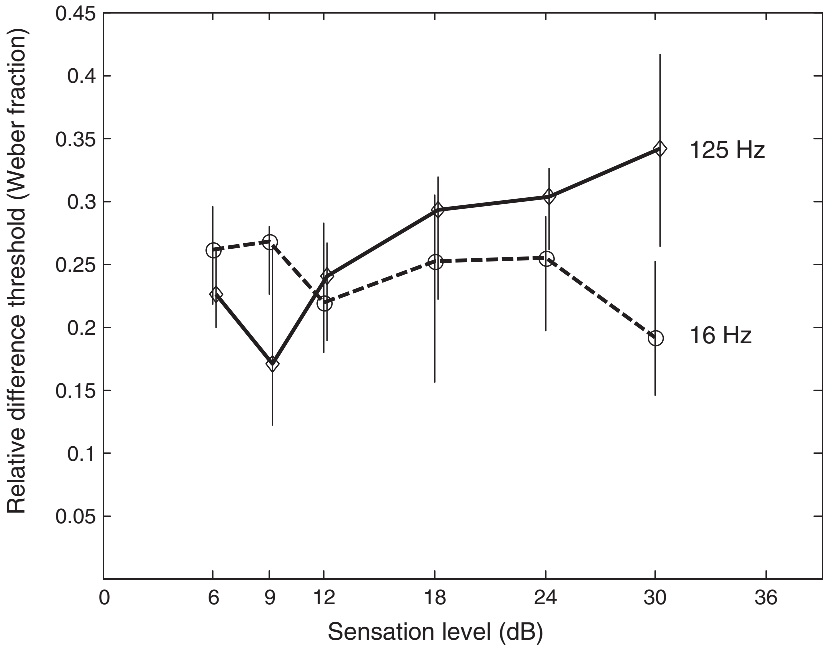

Fig. 4. Median absolute difference thresholds with inter-quartile ranges for 12 subjects at six sensation levels at 16 and 125 Hz.

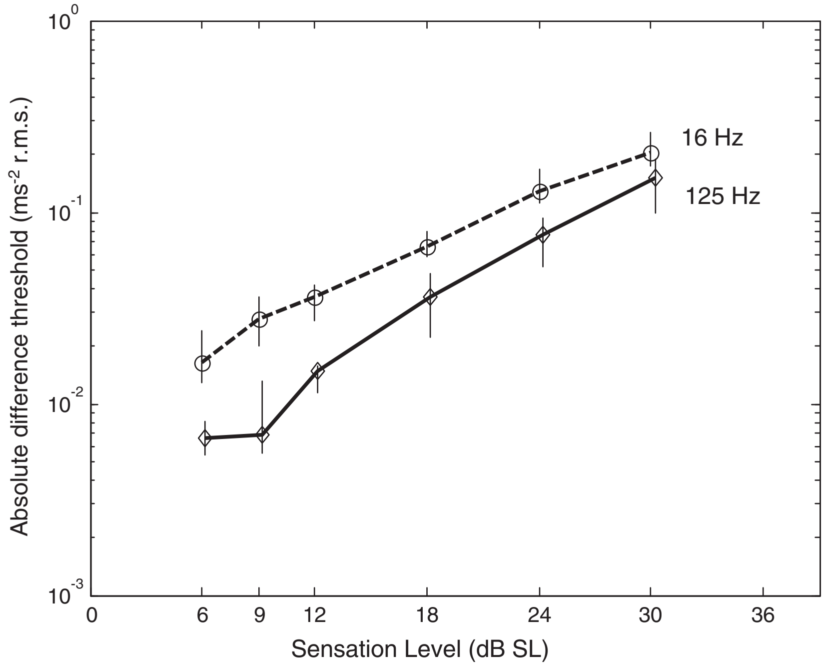

Fig. 5. Median relative difference thresholds and inter-quartile ranges for 12 subjects at six sensation levels at 16 and 125 Hz.

more than predicted by Weber's Law: as the reference magnitude increased by a factor of 16 the difference threshold increased by a factor of 21.

With 16-Hz vibration, the median Weber fractions varied between 0.19 (at 30 dB SL) and 0.27 (at 9 dB SL). With 125-Hz vibration, the median Weber fractions varied between 0.17 (at 9 dB SL) and 0.34 (at 30 dB SL) (Fig. 5).

With 16-Hz vibration, there was no overall statistically significant effect of vibration magnitude on the Weber fractions (Friedman, p=0.4960). Although the median Weber fractions at 6 and 9 dB SL were greater than those at greater magnitudes, the median Weber fraction at 30 dB SL was less than at lower magnitudes.

Table 1
Comparisons between Weber fractions for 125-Hz vibration at magnitudes from 6 to 30 dB SL (p-values, Wilcoxon matched-pairs sign ranks test).

125 Hz	6 dB SL	9 dB SL	12 dB SL	18 dB SL	24 dB SL	30 dB SL
6 dB SL	–	0.2661	0.3804	0.0210*	0.0034**	0.0015**
9 dB SL	–	–	0.3804	0.0161*	0.0049**	0.0161*
12 dB SL	–	–	–	0.0342*	0.0093**	0.0161*
18 dB SL	–	–	–	–	0.3013	0.2036
24 dB SL	–	–	–	–	–	0.3394
30 dB SL	–	–	–	–	–	–

* $p < 0.05$.
** $p < 0.01$.

Table 2
Comparisons between Weber fractions for 16- and 125-Hz vibration at magnitudes from 6 to 30 dB SL (p-values, Wilcoxon matched-pairs sign ranks test).

16 Hz	125-Hz					
	6 dB SL	9 dB SL	12 dB SL	18 dB SL	24 dB SL	30 dB SL
6 dB SL	0.3804	0.1099	0.3394	0.6221	0.2334	0.1099
9 dB SL	0.0425*	0.2334	0.2661	0.6221	0.2661	0.0269*
12 dB SL	0.7334	0.4238	0.8501	0.0771	0.0210*	0.0068**
18 dB SL	0.6221	0.3013	0.9697	0.0522	0.0093**	0.0024**
24 dB SL	0.5186	0.0640	0.4697	0.0771	0.0068**	0.0269*
30 dB SL	0.4238	0.7910	0.2661	0.0122*	0.0024**	0.0034**

* $p < 0.05$.
** $p < 0.01$.

With 125-Hz vibration, the Weber fractions varied with sensation level (Friedman, p=0.0004) with lower Weber fractions at the three lower sensation levels (6, 9, and 12 dB SL) than at the three higher sensation levels (18, 24, and 30 dB SL) (Wilcoxon, $p < 0.04$, Table 1).

Comparison of all Weber fractions obtained for 16-Hz vibration with all the Weber fractions obtained for 125-Hz vibration revealed that the 30 dB SL Weber fractions with 125 Hz were significantly greater than all 16-Hz Weber fractions (Wilcoxon, $p < 0.03$), except those at 6 dB SL. The 24 dB SL Weber fractions obtained with 125-Hz vibration were significantly greater than all 16-Hz Weber fractions (Wilcoxon, $p < 0.03$), except those at 6 and 9 dB SL. The Weber fractions for 16-Hz 9 dB SL were significantly greater than the Weber fractions obtained for 125-Hz 6 dB SL (Wilcoxon, p=0.0425), and the Weber fractions for 16-Hz 30 dB SL were significantly lower than the Weber fractions for 125-Hz 18 dB SL (Wilcoxon, p=0.0122, Table 2).

Within the group of 12 subjects, the Weber fractions for 16-Hz vibration at 18 dB SL and 125-Hz vibration at 24 dB SL were correlated with each other (Spearman, p=0.0082), and the Weber fractions for 16-Hz vibration at 24 dB SL and 125-Hz vibration at 9 dB SL were correlated with each other (Spearman, p=0.0004). There were no other significant correlations between Weber fractions. The correlations were positive other than those between 16-Hz vibration at 6 dB SL and 125-Hz vibration at 12, 18, 24, and 30 dB SL, and those between 16-Hz vibration at 9 dB SL and 126-Hz vibration at 9, 12, 18, and 24 dB SL.

3.3. *Location of sensation*

The reported locations of sensations were simplified by combining the sub-divisions (indicated by lowercase letters in Fig. 2) within locations, since all responses at locations 4 and 5 were either on the sole of the foot (5b and 5c) or at the ankle (4b). Only for the lower leg, the knee, and the upper leg were 'front side' responses (i.e. 3a, 2a and 1a) observed, but there were few responses in these locations compared to other locations. Overall, 'back side' responses were about 90% of the total responses. In Cochran's Q and McNemar tests, the locations from 1 to 4 were combined and compared to the most common reported location (i.e. location 5—sole of the foot).

Fig. 6 shows the reported locations for the strongest sensation. With increasing magnitude of 16-Hz vibration, the sensation of vibration spread from the sole of the foot to the upper part of the foot and the leg. The ratio of the number reporting the strongest sensation at other locations (i.e. 1–4) to the number reporting the sole of the foot (i.e. 5) showed a marginally non-significant change with vibration magnitude at 16 Hz (Cochran's Q, p=0.097). At 125 Hz, irrespective of vibration magnitude, all subjects indicated that they felt the vibration most at the sole of the foot. Comparing the locations giving the strongest sensations between frequencies at each magnitude (e.g. 16 Hz compared with 125 Hz at 6 dB SL), the locations were not significantly different at the two lower magnitudes (i.e. 6 and 9 dB SL; McNemar, p=0.125 for each

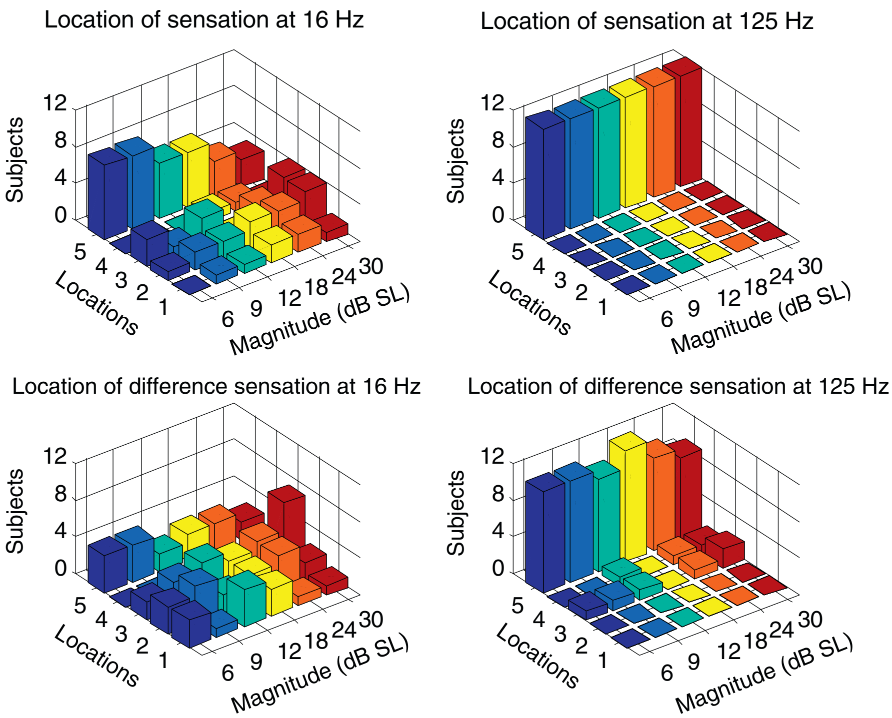

Fig. 6. Number of reported locations of strongest sensations (top graphs) and difference sensations (bottom graphs).

case), but they were significantly different at the two middle magnitudes (i.e. 12 and 18 dB SL; $p=0.031$ for each case), and highly significantly different at the two highest magnitudes (24 and 30 dB SL; $p<0.009$).

Fig. 6 also shows the locations at which subjects reported the differences in sensations that they used to detect differences between the two stimuli (i.e. the locations of the sensations that yielded the difference thresholds). Sensations at the sole of the foot were used for 87.5% of judgements with 125-Hz vibration but only 25% of judgements with 16-Hz vibration. Comparing the locations between frequencies at each magnitude (e.g. 16 Hz compared with 125 Hz at 6 dB SL), the locations differed significantly at all magnitudes (McNemar, $p<0.017$), with changes in the magnitude of 125-Hz vibration detected at the sole of the foot and changes in the magnitude of 16-Hz vibration detected higher up the leg.

The locations at which changes in the vibration magnitude were detected were not significantly different from the locations producing the greatest sensations for either of the two frequencies or any of the six magnitudes (McNemar, $p>0.218$).

4. Discussion

4.1. Absolute thresholds

Median absolute thresholds obtained at the beginning of the sessions in this experiment were 14% lower at 16 Hz and 53% lower at 125 Hz than those obtained by Morioka and Griffin [16]. Although the contact conditions and stimuli were similar, different psychophysical methods were employed in the two studies. Morioka and Griffin used a procedure where the subjects indicated when they perceived the vibration in a single interval ('yes–no' procedure). In the current study, subjects had to detect the vibration in one of two intervals ('forced-choice' procedure). Morioka and Griffin [19] investigated the dependence of vibrotactile thresholds at the fingertip on the psychophysical method and found that the 'forced-choice' procedure significantly lowered thresholds by about 2.2 dB (29% reduction) compared with the 'yes–no' procedure, consistent with the differences observed between the present study and the study by Morioka and Griffin [16]. As suggested by Morioka and Griffin [19], the 'yes–no' procedure requires greater certainty of perception compared with the 'forced-choice' procedure.

The 21% rise in 16-Hz thresholds and the 30% rise in 126-Hz thresholds during the experiment suggest that the modest vibration exposures were sufficient to cause temporary threshold shifts. For the subject with the highest thresholds giving the greatest exposures, the 8-h equivalent vibration exposures according to ISO 5349-1 [20] were less than 0.40 m s^{-2} rms with 16-Hz vibration and less than 0.03 m s^{-2} rms with 125-Hz vibration—much lower than the exposure expected to cause injury. The thresholds might have changed as a result of increased experience at the end of the session, but this would be expected to lower rather than raise thresholds. Whatever the cause of the change, it was small relative to the differences in threshold between subjects (see Fig. 3).

4.2. Weber fractions

Weber fractions most likely to be mediated by the NPI channel (with 16-Hz vibration at 6, 9, and 12 dB SL, according to Bolanowski et al. [3]) were not significantly different from the Weber fractions most likely to be mediated by the P channel (with 125-Hz vibration at 6, 9, and 12 dB SL, according to Bolanowski et al. [3]), except for one marginal case. Although in the conditions investigated any differences in Weber fractions between the two somatosensory channels seem to be small, Fig. 5 suggests a pattern in which the Weber fractions for 125-Hz vibration tend to be less than the Weber fractions for 16-Hz vibration at 6 and 9 dB SL but greater as the vibration magnitude increases.

While the Weber fractions for 16-Hz vibration were consistent with Weber's law (i.e. independent of vibration magnitude), the Weber fractions for 125-Hz vibration appear to contradict Weber's law by being dependent on vibration magnitude. The 125-Hz Weber fractions can be divided into two groups: low sensation levels (6, 9, and 12 dB SL) and high sensation levels (18, 24, and 30 dB SL), with smaller Weber fractions at the lower levels.

The dependence of 125-Hz Weber fractions on vibration magnitude may be due to reduced discriminability within the P channel with increased excitation. The neural responses of Pacinian corpuscles saturate at high magnitudes, which may have increased the 125-Hz difference thresholds. Gescheider et al. [7] reported saturation in the P channel at about 25 dB SL when measuring difference thresholds with 250-Hz vibration applied to the thenar eminence of the hand through a 3-cm^2 contactor. The excitation area and stimulus duration were much greater in the current study and this may have led to saturation of the P channel around 18 dB SL rather than 25 dB SL.

At low magnitudes (6, 9, and 12 dB SL), the 125-Hz difference thresholds are likely to have been mediated by the P channel, while at high magnitudes (18, 24, and 30 dB SL) they may have been mediated by an NP channel, due to saturation in the P channel at levels greater than about 18 dB SL. According to the four-channel model, absolute thresholds of all NP channels are close to each other at 125 Hz, so it is not obvious which NP channel would first take over from the P channel. Comparing Weber fractions for low levels of 16-Hz vibration (probably mediated by the NPI channel) with Weber fractions for low levels of 125-Hz vibration (probably mediated by the P channel), it may be inferred that there was little or no difference in discriminability between the P channel and the NPI channel, suggesting that the greater Weber fractions at high magnitudes of 125-Hz cannot be explained solely by the mediation of changes within the NPI channel if it is Weberian (i.e. has the same Weber fraction at 16 and 125 Hz and at different sensation levels).

A frequency-dependence in the Weber fractions was found at 24 and 30 dB SL (and marginally at 18 dB SL), with 16-Hz Weber fractions significantly lower than 125 Hz Weber fractions. However, this frequency-dependence cannot easily be attributed to a difference between the channels because these high magnitudes are likely to excite multiple channels. It might be assumed that if at these magnitudes the 16- and 125-Hz Weber fractions were mediated by the same NP channel, the Weber fractions would not differ from each other. The difference may therefore have arisen from either the NPI channel having greater discriminability at 16 Hz than at 125 Hz, or mediation by another channel (NP or P).

Although Weber fractions for 125-Hz vibration increased with increasing vibration magnitude, the perception of changes in vibration magnitude was almost always at the sole of the foot. So it seems unlikely that the increase in the 125-Hz Weber fraction was due to a spread in the area of excitation with increasing vibration magnitude. While the location at which the strongest sensation caused by the 16-Hz reference vibration did change with vibration magnitude, the location at which changes in vibration magnitude were perceived did not change with magnitude and the Weber fractions for 16-Hz vibration were independent of vibration magnitude.

A frequency-dependence of the Weber fraction within channels merits consideration (e.g. the NP channel may have a lower Weber fraction with 16-Hz vibration than with 125-Hz vibration). The higher magnitudes of 125-Hz vibration were probably above the absolute threshold of the NP channel and so difference thresholds at the higher magnitudes of 125-Hz vibration may have been mediated by the NPI channel, assuming the P channel had become 'saturated'. So, to compare Weber fractions with similar excitation of the NPI channel, the 16-Hz Weber fractions at 6, 9, and 12 dB SL should be compared with 125-Hz Weber fractions at 18, 24, and 30 dB SL. In this study, the 16-Hz Weber fraction at 6 dB SL was not significantly different from the 125-Hz Weber fractions at any magnitude. The 16-Hz Weber fraction at 9 dB SL was only significantly less than the 125-Hz Weber fraction at 30 dB SL. The 16-Hz Weber fraction at 12 dB SL was significantly less than the 125-Hz Weber fraction at both 24 and 30 dB SL. The absence of systematic differences in Weber fractions between the lowest magnitudes of 16 Hz and the highest magnitudes at 125 Hz allows the possibility that the NPI channel could be responsible for mediating Weber fractions at the higher magnitudes at 125 Hz as well as the lower magnitudes of 16 Hz.

The higher magnitudes of 16-Hz vibration were probably above the absolute threshold of the P channel, so if the P channel has greater discriminability than the NPI channel below 12 dB SL (as may be suggested by the results), the Weber fractions for the higher magnitudes of 16-Hz vibration could have been mediated by the P channel. In which case, involvement of the P channel with high magnitudes of 16-Hz vibration could have contributed to the downward trend in the 16-Hz Weber fractions with increasing magnitude of vibration. If the P channel has a lower Weber fraction than the NPI channel, a reversal of channels may have taken place: Weber fractions for low magnitudes of 16-Hz vibration and high magnitudes of 125-Hz vibration being mediated by the NPI channel and Weber fractions for low magnitudes of 125-Hz vibration and high magnitudes of 16-Hz vibration being mediated by the P channel. Such a reversal could cause significant differences between Weber fractions obtained with high magnitude 125-Hz vibration and low magnitude 125-Hz vibration, and between high magnitude 125-Hz vibration and high magnitude 16-Hz vibration. Below 12 dB SL, there were no significant differences between the channels, but the P-channel Weber fractions (at 125 Hz) tended to be lower than the NPI channel Weber fractions (at 16 Hz).

4.3. Comparison with previous studies

The dependence of Weber fractions on the magnitude of vibration in this experiment is similar to that found for 125-Hz hand-transmitted vibration with a hand grip posture, where at vibration magnitudes less than 12 dB SL the Weber fractions were significantly less than those at higher magnitudes [8]. Unlike the studies by Gescheider et al. ([5,6,7]), but similar to Forta [8], the current study reveals lower Weber fractions for 125-Hz vibration at lower magnitudes but higher Weber fractions at higher magnitudes. Various differences in method may have contributed to the difference in findings. The studies of Gescheider *et al.* involved the application of vibration to small areas of skin at the thenar eminence of the hand whereas the present study applied vibration to the whole foot with the vibration also being transmitted to the leg. Unlike the Gescheider et al. studies, the current experiment did not involve a surround around the contactor with a 1-mm gap—conditions that restrict the distribution of vibration and enhance the sensitivity of the NPI channel. With the contact conditions in the current study, the absolute thresholds of the P-channel may have been lowered by spatial summation [21,22], although the effect of spatial summation on Weber fractions is not known. Gescheider et al. usually employed a small number of highly trained subjects with a wide age range and both genders, whereas the current study had a larger number of untrained subjects with smaller age range and the same gender. While there is some evidence that aging does not affect Weber fractions of the P channel other than at sensation levels slightly above the absolute threshold [23], effects of gender and training cannot be excluded. Gescheider et al. [24] report reductions of up to 50% in Weber fractions when subjects were trained for a period of 23 days. It seems reasonable to expect that the inter-subject variability in difference thresholds reported here would have been greater if the subject group had not been restricted to young and healthy males.

The Gescheider studies, which investigated a wider range of magnitudes than the current study, found a "near-miss" to Weber's Law—a gradual but significant reduction in Weber fractions with increasing sensation level. Since the decline of the thresholds was very gradual, it would not be readily observed with the smaller range of vibration magnitudes investigated here.

The duration of the vibration stimuli also differed between the present study and the Gescheider et al. studies. Similar to spatial summation, temporal summation of the P channel also reduces absolute thresholds [25]. With 250-Hz vibration varying from 10 to 700 ms in duration applied to the thenar eminence of the hand, Gescheider et al. [6] investigated the effects of stimulus duration on Weber fractions using both a gated-pedestal method (i.e. with a pause between the two measurement intervals) and a continuous pedestal method (with no pause between the measurement intervals). They found that the Weber fractions were not affected by duration when the gated-pedestal method was employed, but that Weber fractions decreased with increasing stimulus duration when the continuous pedestal method was employed. The present study also used the gated-pedestal method, but had stimulus durations of 2000 ms, much longer than the maximum duration used by Gescheider et al. The longer stimulus duration in the current experiment may have contributed to saturation of the P channel at lower levels. The frequencies of vibration used in the two studies (250 Hz by Gescheider et al. and 125 Hz in the present study) both excite the P channel over a wide range of magnitudes, but there may be differences due to the use of the different frequencies.

5. Conclusions

For sensation levels from 6 to 30 dB, median Weber fractions for 16-Hz vertical sinusoidal vibration of the foot are in the range 0.19 (at 30 dB SL) to 0.27 (at 9 dB SL). For 125-Hz vibration, Weber fractions are in the range 0.17 (at 9 dB SL) to 0.34 (at 30 dB SL). Although the 16-Hz Weber fractions were independent of vibration magnitude, the 125-Hz Weber fractions were significantly smaller at lower sensation levels (6, 9, and 12 dB SL) than at higher sensation levels (18, 24, and 30 dB SL). Increases in the 125-Hz Weber fractions at greater magnitudes may have been caused by reduced discriminability in the P channel with increased excitation, or because Weber fractions for 125-Hz vibration at levels greater than about 18 dB SL were not being mediated by the P channel but by one or more NP channels.

At vibration magnitudes slightly in excess of absolute thresholds (i.e. 6 to 12 dB SL), Weber fractions obtained from the NPI channel (at 16 Hz) and the P channel (at 125 Hz) were similar but with some evidence for slightly greater Weber fractions with 16-Hz vibration at the lowest magnitudes. At 24 and 30 dB SL, the 125-Hz Weber fractions were greater than the 16-Hz Weber fractions, possibly due to changes in the channels mediating Weber fractions at higher magnitudes.

Spreading of the sensation to a wider area at higher magnitudes of 16-Hz vibration did not cause significant differences in the 16-Hz Weber fractions.

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