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Vibrotactile difference thresholds: effects of vibration frequency, vibration magnitude, contact area and body location

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Abstract *[254 words]*

It has not been established whether the smallest perceptible change in the intensity of vibrotactile stimuli depends on the somatosensory channel mediating the sensation. This study investigated intensity difference thresholds for vibration using contact conditions (different frequencies, magnitudes, contact areas, body locations) selected so that perception would be mediated by more than one psychophysical channel. It was hypothesised that difference thresholds mediated by the non-Pacinian I (NPI) channel and the Pacinian (P) channel would differ. Using two different contactors (1-mm diameter contactor with 1-mm gap to a fixed surround; 10-mm diameter contactor with 2-mm gap to the surround) vibration was applied to the thenar eminence and the volar forearm at two frequencies (10 and 125 Hz). The up-down-transformed-response method with a three-down-one-up rule provided absolute thresholds and also difference thresholds at various levels above the absolute thresholds of 12 subjects (i.e. sensation levels, SLs) selected to activate preferentially either single channels or multiple channels. Median difference thresholds varied from 0.20 (thenar eminence with 125-Hz vibration at 10 dB SL) to 0.58 (thenar eminence with 10-Hz vibration at 20 dB SL). Median difference thresholds tended to be lower for the P channel than the NPI channel. The NP II-channel may have reduced difference thresholds with the smaller contactor at 125 Hz. It is concluded that there are large and systematic variations in difference thresholds associated with the frequency, the magnitude, the area of contact, and the location of contact with vibrotactile stimuli that cannot be explained without increased understanding of the perception of supra-threshold vibrotactile stimuli.

Abstract *[78 words]*

Intensity difference thresholds were obtained for 12 subjects at the thenar eminence and the volar forearm using two contactors (1-mm diameter with 1-mm gap to fixed surround; 10-mm diameter with 2-mm gap to surround) at two frequencies (10 and 125 Hz) at various sensation levels. Systematic variations in difference thresholds (from 0.20 to 0.58) associated with frequency, magnitude, area of contact, and location of contact cannot be explained without increased understanding of the perception of supra-threshold vibrotactile stimuli.

1. Introduction

The difference threshold, or the 'just noticeable difference', is the difference in value of two stimuli that is just sufficient for the difference to be detected ('Unterschiedsempfindlichkeit' in Fechner 1860). Psychophysicist E. H. Weber proposed a law which states that relative difference thresholds expressed as fractions are constant values:

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

where I denotes stimulus intensity and ΔI is the absolute difference threshold (Fechner 1860). For vibration, I and ΔI can be expressed in units of displacement, velocity, or acceleration.

Difference thresholds can assist the design of man-machine interfaces and the optimisation of comfort in transport. In order to change comfort or convey information, a vibration must altered by an amount that is sufficient for the change to be perceived. In transport, it may be assumed that any single change in vibration intensity less than the difference threshold will not alter passenger assessment of ride comfort, so Weber fractions inform designers of the minimum improvement necessary for a change to be appreciated.

Building on research that established three-channel models of vibrotactile perception (Capraro *et al*., 1979; Gescheider *et al*., 1985), Bolanowski *et al*. (1988) and Gescheider *et al*. (2001) suggested four channels are involved in the perception of vibration through glabrous skin. The four channels are associated with four types of low-threshold mechanoreceptive fibers innervating the glabrous skin as described in neurophysiological studies (reviewed in Vallbo and Johansson, 1984). According to the four-channel model developed from studies at the thenar eminence of the hand, vibration at frequencies less than about 2 Hz is perceived first by the slow-adapting non-Pacinian III channel. The fast-adapting non-Pacinian I channel normally mediates absolute thresholds between approximately 2 and 40 Hz. At frequencies greater than about 40 Hz, absolute thresholds are mediated by the fast-adapting Pacinian channel, which has a sensitivity to displacement that increases with increasing frequency up to about 250 Hz and then declines, describing a U-shaped frequency-dependence. The fourth channel, slow-adapting non-Pacinian II, is sensitive in a frequency range similar to the P channel, but has less sensitivity than the P channel in most contact conditions. Understanding of the channels involved in the perception of vibration on non-glabrous skin is more limited.

The receptors of the Pacinian channel are Pacinian nerve endings that are found in both glabrous and hairy skin, and in some other tissues such as tendons. Receptors of the non-Pacinian I channel are the Meissner nerve endings that are found in glabrous skin. Absolute thresholds for the perception of vibration at the volar forearm and the thenar eminence have been found to differ by 11 dB at 25 Hz and about 20 dB at 125 Hz, when measured using a contactor 16.6 mm in diameter, with the difference attributed to differences in receptor densities at the two sites (Verrillo 1966).

Although absolute thresholds vary according to the somatosensory channel, there are differing reports as to whether difference thresholds depend on the somatosensory channel. Craig (1972) applied 160-Hz sinusoidal vibration to the fingertip through a 6-mm diameter circular contactor at four vibration magnitudes (14, 21, 28, and 35 dB SL) and found relative difference thresholds constant at about 0.16, consistent with Weber's Law. For the perception of vibration of a handle at each of seven frequencies (8, 16, 31.5, 63, 125, 250, 500 Hz) mean relative difference thresholds of 0.18 at 2.0 ms^{-2} r.m.s. and 0.15 at 5.0 ms^{-2} r.m.s. have been found, with no significant dependence on vibration frequency (Morioka 1998).

Some studies have found that, contrary to Weber's Law, the magnitude of the vibration affects relative difference thresholds. With sinusoidal vibration applied by a 19.2-mm contactor to the thenar eminence of the hand, Gescheider *et al*. (1990) found reductions in difference thresholds with increasing vibration magnitude, from about 0.26 at 4 dB SL to 0.12 at 40 dB SL (where SL is the sensation level – the level above the absolute threshold of perception of the subject), with similar relative difference thresholds at 25 Hz and 250 Hz (differing by less than about 0.05). Gescheider *et al*. (1996a) found that relative difference thresholds for 250-Hz sinusoidal vibration applied to the thenar eminence decreased from about 0.26 at 4 dB SL to about 0.16 at 36 dB SL. A reduction in the relative difference thresholds with increasing vibration magnitude was also reported in Gescheider *et al*. (1997) with skin temperatures of 20, 30, and 40°C. At all three temperatures the relative difference thresholds reduced from about 0.23 at 4 dB SL to 0.13 at 42 dB SL.

Using a hand gripping posture and 125-Hz sinusoidal vibration, relative difference thresholds have been found to increase as the vibration magnitude increased from 12 dB SL to 36 dB SL, although there was no significant effect of vibration magnitude with 16-Hz vibration (Forta *et al*. 2007).

Some of the differences in relative difference thresholds found by Gescheider *et al.* (1990) and Forta *et al.* (2007) could be due to mediation by different channels. The absence of statistically significant effects in the other studies (e.g. Morioka, 1998; Craig, 1972) might be attributed to the higher vibration magnitudes used in those experiments stimulating an unknown mix of channels. It is therefore not clear from the literature whether difference thresholds depend on the channel mediating the sensation of vibration. The objective of the experiment described here was to investigate the dependence of intensity difference thresholds for sinusoidal vibration on the somatosensory channel mediating the threshold. The vibration frequencies of 10 Hz and 125 Hz were selected so as to preferentially excite the non-Pacinian I channel (with 10 Hz vibration) and the Pacinian channel (with 125 Hz vibration) when vibration at the thenar eminence was 10 dB above the absolute threshold. It was hypothesised that the relative difference thresholds (i.e., Weber fractions) would differ between the NPI and P channels. Relative difference thresholds were also measured with vibration sensation levels greater than 10 dB, so as to recruit multiple channels simultaneously, and on the hairy skin of the volar forearm, so as to compare relative difference thresholds obtained with other channels.

2. Method

2.1. Apparatus

An *HVLab* Vibrotactile Perception Meter (VPM) incorporating an electro-dynamic vibrator was used to produce the vibration stimuli. Vibration signals were generated and measured using a specially written programme in *HVLab* software (version 3.81) running on a personal computer. The signals from the PC were generated at 5000 samples per second. Vibration was measured using a piezo-electric accelerometer integrated in the VPM contactor. The acceleration of the contactor was acquired via a PCL-818 12-bit analogue to digital converter and Techfilter anti-aliasing filter set at 1000 Hz.

Two different contactors were used in the experiment. Both were circular in shape, one 1-mm in diameter and the other 10-mm in diameter. Both contactors had circular surrounds, with the gap between the 1-mm contactor and its surround 1 mm, and the gap between the 10-mm contactor and its surround 2 mm.

The VPM controller had a built-in display that allowed the monitoring of the force applied by the subject to the surround. The controller also had a built-in thermocouple and temperature display.

2.2. Subjects and Postures

To limit the number of variables, the current study was conducted on healthy male subjects in a narrow age range. There are few studies of the effects of age and gender on difference thresholds, but according to Gescheider *et al*. (1996b), relative difference thresholds for vibrotactile stimuli are independent of age other than at sensation levels only slightly above absolute threshold.

Twelve subjects aged 19 to 28 (mean 24 years, mean stature 179 cm, mean weight 72.5 kg), took part in the experiment. They were healthy right-handed males, all students of the University of Southampton. The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

Absolute thresholds and difference thresholds were determined at two locations: on the thenar eminence of the right hand and on the right volar forearm 12 cm from the wrist crease on the ulnar side over the flexor digitorum profundus muscle. The location on the volar forearm was marked with a pen to allow relocation at the same spot on the second session on the following day.

Skin temperatures were measured at the two locations at the beginning and the end of test sessions. Tests commenced when the skin temperature at the test location was greater than 30°C, as skin temperature affects the absolute thresholds of the Pacinian channel (Verrillo and Bolanowski 1986).

When determining absolute thresholds and difference thresholds, subjects applied a constant force of 2 N to the surround. The subjects and the experimenter monitored the applied force on the display of the VPM controller.

During measurements, the subjects were presented with white noise at 65 dBA through headphones so as to mask any aural cues or distractions.

With the arm resting on a support on one table, the subject's thenar eminence made contact with the VPM resting on a different table. The fingers rested on a foam surface on the same table as the VPM. For the tests at the forearm, the arrangement was the same except the arm rest supported the arm nearer to the elbow. Subjects were instructed to maintain the same posture throughout the experiment (Figure 1).

FIGURE 1 ABOUT HERE

2.3. Sessions

Each subject attended four sessions of about 80 minutes. Absolute thresholds were obtained in the first and the third sessions, with one session per contactor. Two measurements of the absolute threshold were obtained for each frequency (10 and 125 Hz) at each location (thenar eminence and the volar forearm) in each session.

The absolute thresholds obtained in the first and third sessions were used to calculate the reference magnitudes at which difference thresholds were obtained in the second and fourth sessions. At both frequencies, difference thresholds were measured at two sensation levels at the thenar eminence and one sensation level at the volar forearm. Six difference thresholds were obtained for one contactor in one session (four on the thenar eminence and two on the volar forearm) (Table 1). In order to keep the waveform distortion to a minimum (5 to 10%) at all frequencies and magnitudes, different sensation levels were used for different contact areas, contact locations, and vibration frequencies. Some subjects had high absolute thresholds in some conditions, leading to higher absolute magnitudes.

TABLE 1 ABOUT HERE

2.4. Psychophysical methods and vibration stimuli

The 10-Hz and 125-Hz stimuli were 1-second sinusoids with 0.1-second cosine tapered rise and decay times.

The up-down-transformed-response (UDTR) method was used to determine both the absolute thresholds and the difference thresholds (Wetherill and Levitt 1965). In this method, the magnitude of the test stimulus is determined by the responses of the subject. The stimuli were presented in two intervals, and the magnitude of the test stimulus was determined using the three-down-one-up rule: if the subject gave three consecutive correct responses the level of the test stimulus was reduced by one step, if the subject gave an incorrect response level of the test stimulus was increased by one step. A red light was used to indicate the duration of the stimuli.

When determining absolute thresholds, one of the two 1-s intervals contained the test stimulus, while the other interval did not contain a stimulus. A 1-second pause separated the two intervals. The interval containing the test stimulus was determined randomly in each trial. The subject's task was to identify 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 1 dB. In the first trial, the stimulus started at a magnitude where the subjects were able to feel the vibration.

The difference thresholds were also determined using a two-interval-forced-choice technique. However, one interval contained the test stimulus and the other a reference stimulus. The order of the test stimulus and the reference stimulus was randomly determined for each trial. The test vibration was always at a greater magnitude 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 0.33 dB. Subjects were asked to identify the interval that contained the stronger stimulus. In the first trial, the difference was great enough to be detected by all subjects.

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 absolute thresholds and the difference thresholds were calculated from the average of the final four reversals, ignoring the first two reversals, using the measured r.m.s. accelerations of the reference and test vibrations at the reversal points. To determine a relative difference threshold, the absolute value of the difference threshold for that stimulus was divided by the r.m.s. acceleration magnitude of the reference vibration.

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 test and the Wilcoxon matched-pairs signed ranks test for two-related samples) were employed in the statistical analysis.

3. Results

3.1 Absolute Thresholds

For both frequencies and both locations, absolute thresholds measured with the 10-mm diameter contactor were significantly lower than thresholds measured with the 1-mm diameter contactor (p<0.001, Wilcoxon; Figure 2). For both frequencies, thresholds at the volar forearm were significantly greater than thresholds measured at the thenar eminence (p<0.0005, Wilcoxon).

FIGURE 2 ABOUT HERE

Thresholds obtained in two different conditions but mediated by the same channel may be expected to be correlated: subjects with a higher threshold in one condition would tend to have a higher threshold in the other condition. At each frequency and location, 1-mm and 10-mm thresholds were uncorrelated, except on the volar forearm at 125 Hz (p=0.0145, Spearman). Between locations and frequencies, 1-mm and 10-mm thresholds were also uncorrelated, except between 1-mm 10-Hz thresholds on the thenar eminence and 10-mm 125-Hz thresholds on the volar forearm (p=0.0032).

With the 1-mm contactor, thresholds across conditions were uncorrelated, except between 10-Hz at the thenar eminence and 125 Hz on the volar forearm (p=0.010). With the 10-mm contactor, there were no significant correlations across conditions.

3.2. Difference Thresholds

Median relative difference thresholds are shown in Figure 3. The results of statistical tests over all conditions are reported in Table 2.

FIGURE 3 AND TABLE 2 ABOUT HERE

Comparing relative difference thresholds likely to arise from the NPI channel (1-mm contactor: thenar eminence, 10 Hz, 10 dB SL) with relative difference thresholds likely to arise from the P channel (10-mm contactor: thenar eminence, 125 Hz, 10 dB SL), there were lower relative difference thresholds for the P channel (median 0.36) than the NPI channel (median 0.52), with the difference marginally not significant (p=0.064, Wilcoxon). Relative difference thresholds for the P channel (10-mm contactor: thenar eminence, 125 Hz, 10 dB SL) were significantly greater than those obtained with the same conditions but a higher magnitude (10-mm contactor, thenar eminence, 125 Hz, 15 dB SL) (p=0.0425, Wilcoxon), and greater than those obtained with the smaller contactor (1-mm contactor: thenar eminence, 125 Hz) at both 10 dB (p=0.0049, Wilcoxon) and 30 dB (p=0.0093, Wilcoxon).

Effect of frequency of vibration

At the thenar eminence, with both the 1-mm and the 10-mm contactor the difference thresholds were significantly greater with 10-Hz vibration than with 125-Hz vibration (p<0.01, Wilcoxon), except for the 10-mm contactor at 10 dB SL (p=0.850, Wilcoxon). At the volar forearm, there was no significant effect of frequency with the 1-mm contactor (p=0.092, Wilcoxon) or the 10-mm contactor (p=0.5186, Wilcoxon; Figure 3).

Effect of contactor size

The contactor affected difference thresholds on the thenar eminence: with 10 Hz at 10 dB SL the difference thresholds were lower with the 10-mm contactor (p=0.0269, Wilcoxon), whereas with 125 Hz at 10 dB SL the difference thresholds were lower with the 1-mm contactor (p=0.0049, Wilcoxon; Figure 3). There was no significant effect of the contactor with other conditions at the thenar eminence or on the volar forearm. The difference thresholds obtained using the two sizes of contactor were not correlated with each other in any of the six conditions shown in Figure 3 (p>0.055, Spearman).

Effect of magnitude of vibration

At the thenar eminence, difference thresholds were determined at two magnitudes for both frequencies and both contactor sizes, and are shown as a function of vibration magnitude (dB SL) in Figure 4. There was no effect of magnitude on difference thresholds, except with the 10-mm contactor at 125 Hz, where difference thresholds decreased with increasing magnitude from 10 to 15 dB SL (p=0.0425, Wilcoxon).

FIGURE 4 ABOUT HERE

Effect of contact location

Relative difference thresholds at the thenar eminence and the volar forearm are compared in Figure 5. At each frequency and contactor size, the difference thresholds did not differ between the two locations.

FIGURE 5 ABOUT HERE

4. Discussion

4.1. Absolute Thresholds

At the thenar eminence with 10-Hz vibration and a 19.2-mm diameter contactor, Bolanowski *et al*. (1988) reported median absolute thresholds of 20 dB (in peak displacement re 1 micrometer), which may be compared with 20.3 dB in the current study with the 10-mm diameter and 22.3 dB with the 1-mm diameter contactor. With 125-Hz vibration with a 19.2-mm contactor, Bolanowski *et al*. (1988) reported thresholds of about -10 dB compared to -4.4 dB with the 10-mm contactor and 11.5 dB with the 1-mm contactor in the present study. The differences between the studies are likely to be partially due to the different sizes of the contactors. With 125-Hz vibration, the threshold is mediated by the P channel, which has a spatial summation capability (Verrillo 1963, 1965, 1966, 1985; Morioka and Griffin 2005). Assuming a threshold reduction of 3 dB per doubling of area (Verrillo 1963), and using thresholds from Bolanowski *et al*. (1988), the larger contactor in this experiment would be expected to produce a threshold of -6.4 dB, closer to the measured threshold of -4.4 dB than the -10 dB that Bolanowski *et al*. obtained with the 19.2-mm contactor. The psychophysical method used in the present study estimated the thresholds for 79.4% correct detection on the psychometric function compared to 75% in the study by Bolanowski *et al*. (1988), so were likely to produce slightly higher thresholds. There were also differences between the subject populations: 12 untrained young males in the present study and five trained subjects of both genders and a wider age range in Bolanowski *et al*. (1988).

With 125-Hz vibration at the thenar eminence in the current study, absolute thresholds were about 16 dB lower with the 10-mm contactor than with the 1-mm contactor, consistent with spatial summation in the P channel. With 10-Hz vibration at the thenar eminence, absolute thresholds with the 10-mm contactor were about 2.5 dB lower than with the 1-mm contactor. Since the NPI channel does not have spatial summation capability, the dependence on contactor size was possibly due to a lower chance of the 1-mm contactor being placed in the field of a sensitive mechanoreceptor.

The lower absolute thresholds at the thenar eminence than at the volar forearm may be due to a greater density of mechanoreceptors in the glabrous skin of the thenar eminence than the hairy skin of the volar forearm. With the 1-mm contactor, the absolute thresholds were about 11 dB greater at the volar forearm at 10 Hz, and about 9.2 dB greater at 125 Hz. With the 10-mm contactor, the volar forearm thresholds were greater by 4.6 dB at 10 Hz and by 10.1 dB at 125 Hz. At both frequencies, these differences between absolute thresholds at the thenar eminence and the volar forearm are somewhat less than the differences found by Verrillo (1966).

At the thenar eminence, absolute thresholds obtained with different conditions (i.e. different frequencies and different contactors) were uncorrelated, indicating that either they were mediated by different channels or, if they were mediated by the same channel, other factors (e.g. contact location) had greater influences on the relative sensitivity of subjects. Significant correlations between 125-Hz thresholds obtained with the two sizes of contactor on the volar forearm suggest the same channel mediated perception.

4.2. Difference Thresholds

Relative difference thresholds measured in this study were generally greater than those found in other studies. Craig (1972), Morioka (1998), and Forta *et al*. (2007) reported relative difference thresholds between 0.15 and 0.20, whereas the lowest median difference threshold in this study was 0.20 and the highest was 0.58. Morioka (1998) and Forta *et al*. (2007) determined difference thresholds for the whole hand, where the transmission of vibration away from the skin in contact with the source of vibration may have offered more cues for detecting differences than the small area of skin excited in the current study. Craig (1972) employed a 6-mm diameter contactor protruding through an 8-mm diameter surround and determined difference thresholds for the fingertips of two trained female subjects, compared to the 12 untrained males in the current study.

Gescheider *et al*. (1990, 1994, 1996a, 1997) used similar contact conditions to the current experiment and reported a relative difference threshold of about 0.24 when using a 19.2-mm contactor (19.2-mm diameter) and 250-Hz vibration, similar to the current experiment with the 10-mm diameter contactor and 125-Hz vibration at 15 dB SL (i.e., 0.24), but much lower than at 10 dB SL (i.e., 0.36). Gescheider *et al*. (1990) also found relative difference thresholds of about 0.24 using a 19.2-mm contactor with 25-Hz vibration at 10 dB SL, lower than the 0.40 found in the current study with the 10-mm contactor at 10 Hz. At 20 dB SL, the difference between the studies is even greater.

Unlike the studies of Morioka (1998), Craig (1972) and Forta *et al* (2007), the Gescheider *et al.* studies reported a reduction in relative difference thresholds with increasing vibration magnitude. The reduction was observed over the range 4 to 40 dB SL. The current study found a dependence on sensation level only at 125 Hz when the 10-mm contactor was applied to the thenar eminence of the hand. No significant dependence on vibration magnitude was observed in other conditions. The current study used vibration sensation levels from 10 to 30 dB, which describe a narrower range than the 4 to 40 dB SL used by Gescheider *et al*. The dependence on sensation level observed in the Gescheider *et al* studies is less in the 10-30 dB SL range.

Differences in relative difference thresholds between the current study and the Gescheider *et al*. studies may be due to differences between the subjects (small number of trained subjects but a wide age range and mixed genders employed in the Gescheider *et al*. studies compared to 12 untrained young male subjects in the current experiment). Gescheider *et al*. (2009) reported that practice improves performance in difference discrimination tasks, with a reduction in the difference thresholds up to 50% after a training period of 23 days. This suggests the use of highly trained subjects by Gescheider *et al*. may have contributed to their lower relative difference thresholds.

It was hypothesised that relative difference thresholds on the thenar eminence obtained with mediation solely within the P-channel (using the 10-mm diameter contactor and 125-Hz vibration at 10 dB SL) would differ from relative difference thresholds mediated solely within the NPI-channel (using the 1-mm diameter contactor and 10-Hz vibration at 10 dB SL). The relative difference thresholds were lower for the P-channel (median = 0.36) than the NPI channel (median = 0.52), but the difference was marginally non-significant. This indicates that if there are differences between the discriminative capabilities of the two channels, the difference was too small to be seen clearly in this experiment because it was obscured by the influence of other factors.

The difference thresholds were dependent on the frequency of vibration with the 1-mm contactor but not with the 10-mm contactor: the 1-mm difference thresholds were lower for 125-Hz vibration than 10-Hz vibration. This might be due to the involvement of the NPI channel at 10 Hz and the P channel at 125 Hz, or the NPII channel may be involved at 125 Hz. Gescheider *et al*. (1997) suggest the NPII channel might have a lower relative difference threshold than the P channel, which in turn implies that the NPII channel may have been responsible for the low difference thresholds at the thenar eminence with the 1-mm contactor at 125-Hz and 10 dB SL, and at higher sensation levels with both contactors.

At 125-Hz and 10 dB SL, the difference thresholds at the thenar eminence were lower with the 1-mm contactor than the 10-mm contactor, consistent with lower relative difference thresholds for the NPII channel than the P channel. With higher sensation levels at the thenar eminence, the relative difference thresholds at 125 Hz were similar for the 1-mm and 10-mm contactors. According to the four-channel model of Bolanowski *et al*. (1988), the difference between the absolute thresholds of the P and the NPII channels is about 25 dB SL at 125 Hz on the thenar eminence. The higher sensation level used in the current experiment was 30 dB SL with the 1-mm contactor, high enough to excite the NPII channel. However, with the 10-mm contactor the higher level (15 dB SL) may not have excited the NPII channel. The 2-mm gap to the surround with the 10-mm contactor was larger than used in other studies and with the 1-mm contactor in the present study, possibly increasing the NPII threshold since the NPII channel is sensitive to skin stretch. However, the contact area was smaller (0.8 cm^2) than used by Bolanowski *et al*. and Gescheider *et al*. (2.9 cm^2), so higher P-channel thresholds would be expected in the present study, reducing the difference between the absolute thresholds of the P and NPII channels. Whether a rise in NPII thresholds (due to the greater surround gap) or a rise in P thresholds (due to reduced contact area) reduced the separation between the thresholds of the two channels to less than the 25 dB reported by Bolanowski *et al*. (1988), is unclear. It is therefore uncertain whether 15 dB SL was sufficient to excite the NPII channel at the thenar eminence when the 10 mm contactor was employed.

The smaller relative difference thresholds with the 1-mm contactor than the 10-mm contactor at 125 Hz might have been caused by the involvement of the NPII channel: the reduced excitation area and reduced gap between the contactor and the surround with the 1-mm contactor was more likely to excite the NPII channel, compared to the 10-mm contactor with the 2-mm gap. Such involvement of the NPII channel would be consistent with the relative difference thresholds being lower for 125-Hz vibration than for 10-Hz vibration when the 1-mm contactor was used.

5. Conclusions

There are large and systematic changes in relative difference thresholds associated with changes in the frequency, the magnitude, the area of contact, and the location of contact with vibrotactile stimulation. There is evidence suggesting relative difference thresholds may be lower for the P-channel than the NPI channel. However, current understanding leaves doubts as to the involvement of the P, NPI, and NPII channels in the perception of supra-threshold vibrotactile stimulation, leaving uncertainty as to the extent to which changes in difference thresholds can be attributed to differences in relative difference thresholds between channels.

Declaration of interests:

The authors report no conflicts of interest.

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Tables

Table 1. Conditions for difference threshold measurements.

Table 2. Significance of differences between relative difference thresholds (*p*-values for Wilcoxon tests): * $p<0.05$, ** $p<0.01$. TE = thenar eminence; VF = volar fore-arm.

Table 1. Conditions for difference threshold measurements.

Contactor diameter (mm)	Gap (mm)	Location	Frequency (Hz)	Magnitude (dB SL)
1	1	Thenar eminence	10	10
				20
			125	10
				30
		Volar forearm	10	10
			125	5
10	2	Thenar eminence	10	10
				20
			125	10
				15
		Volar forearm	10	10
			125	10

Table 2. Significance of differences between relative difference thresholds (*p*-values for Wilcoxon tests): * *p*<0.05, ** p<0.01. TE = thenar eminence; VF = volar fore-arm.

				1-mm diameter contactor					
				Thenar eminence (TE)				Volar forearm (VF)	
				10 dB	10 dB	20 dB	30 dB	10 dB	5 dB
Contactor diameter (mm)	**Location**	**Level (dB)**	**Frequency (Hz)**	**10 Hz**	**125 Hz**	**10 Hz**	**125 Hz**	**10 Hz**	**125 Hz**
1	**TE**	**10**	**10**	--	0.0015**	1.0000	0.0015**	0.9097	0.0342*
		10	**125**		--	0.0024**	0.9097	0.0024**	0.1294
		20	**10**			--	0.0034**	0.9097	0.1099
		30	**125**				--	0.0015**	0.1099
	VF	**10**	**10**					--	0.0923
		5	**125**						--
10	**TE**	**10**	**10**	0.0269*	0.0005**	0.0640	0.0640	0.1294	0.4238
		10	**125**	0.0640	0.0049**	0.1294	0.0093**	0.2334	0.8501
		20	**10**	0.0640	0.0034**	0.2036	0.0093**	0.3804	0.2036
		15	**125**	0.0010**	0.3013	0.0049**	0.7910	0.0049**	0.1514
	VF	**10**	**10**	0.5186	0.0010**	0.6221	0.0093**	0.8501	0.1099
		10	**125**	0.3804	0.0093**	0.3804	0.0161*	0.6773	0.4697
				10-mm diameter contactor					
				Thenar eminence (TE)				**Volar forearm (VF)**	
				10 dB	**10 dB**	**20 dB**	**15 dB**	**10 dB**	**10 dB**
				10 Hz	**125 Hz**	**10 Hz**	**125 Hz**	**10 Hz**	**125 Hz**
10	**TE**	**10**	**10**	--	0.8501	0.2036	0.0093**	0.1099	0.6221
		10	**125**		--	0.3804	0.0425*	0.0342*	0.4238
		20	**10**			--	0.0024**	0.4697	0.7910
		15	**125**				--	0.0015**	0.0640
	VF	**10**	**10**					--	0.5186
		10	**125**						--

Figure Captions

Figure 1 Posture and set-up used in the experiment**.**

Figure 2 Absolute thresholds (medians of 12 subjects) and the inter-quartile ranges for 10 Hz and 125 Hz determined at the thenar eminence and at the volar forearm ● 1-mm diameter contactor; o 10-mm contactor.

Figure 3 Effect of frequency and contactor size on relative difference thresholds (medians of 12 subjects): ● 1-mm diameter contactor; o 10-mm contactor. Sensation levels shown next to median thresholds.

Figure 4 Effect of vibration magnitude (in dB SL) on the relative difference thresholds for 10 Hz and 125 Hz at the thenar eminence. Medians of 12 subjects and inter-quartile ranges are shown. ● 1-mm diameter contactor; o 10-mm contactor.

Figure 5 Effect of body location (thenar eminence and the volar forearm) on the relative difference threshold at 10 Hz and 125 Hz. Medians of 12 subjects and inter-quartile ranges are shown. ● 1-mm diameter contactor; o 10-mm contactor.

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Somatosensory and Motor Research. 29, 1, p. 28-37.

Figures

Figure 1 Posture and set-up used in the experiment.

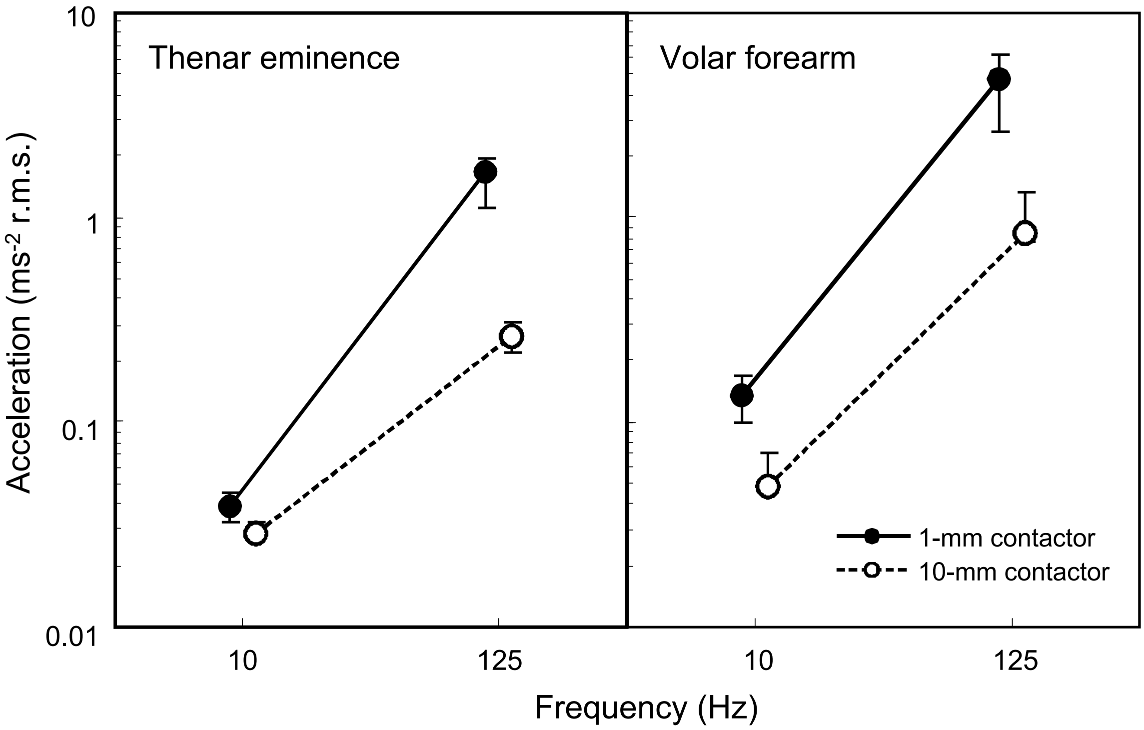

Figure 2. Absolute thresholds (medians of 12 subjects) and the inter-quartile ranges for 10 Hz and 125 Hz determined at the thenar eminence and at the volar forearm ● 1-mm diameter contactor; o 10-mm contactor.

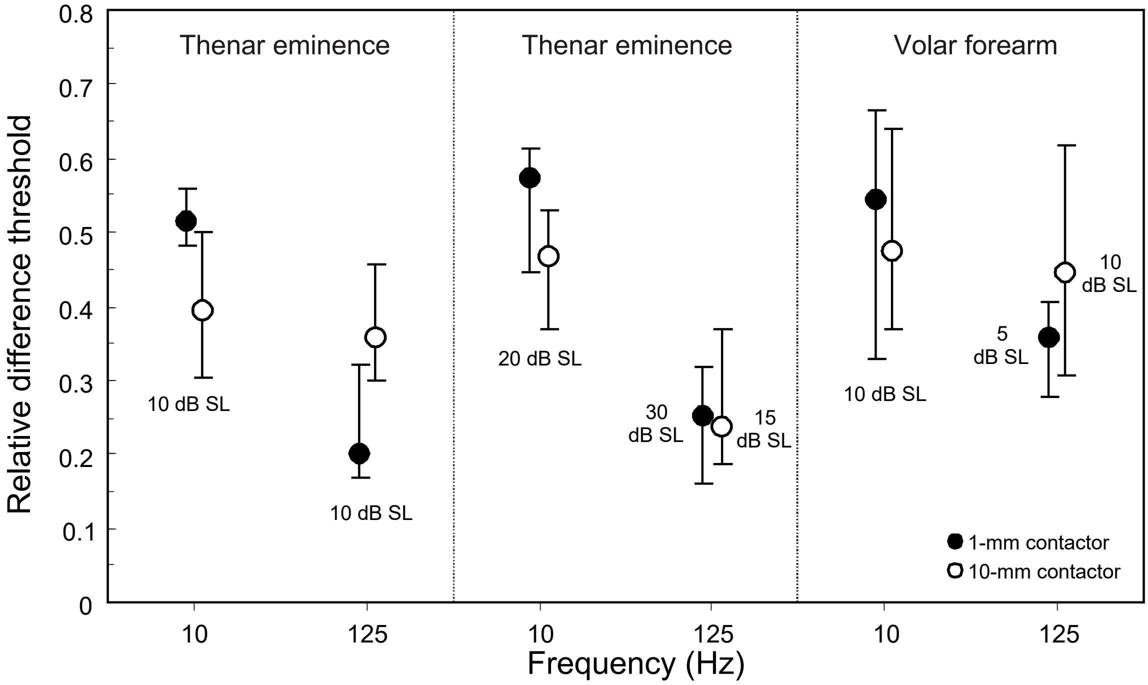

Figure 3. Effect of frequency and contactor size on relative difference thresholds (medians of 12 subjects): ● 1-mm diameter contactor; o 10-mm contactor. Sensation levels shown next to median thresholds.

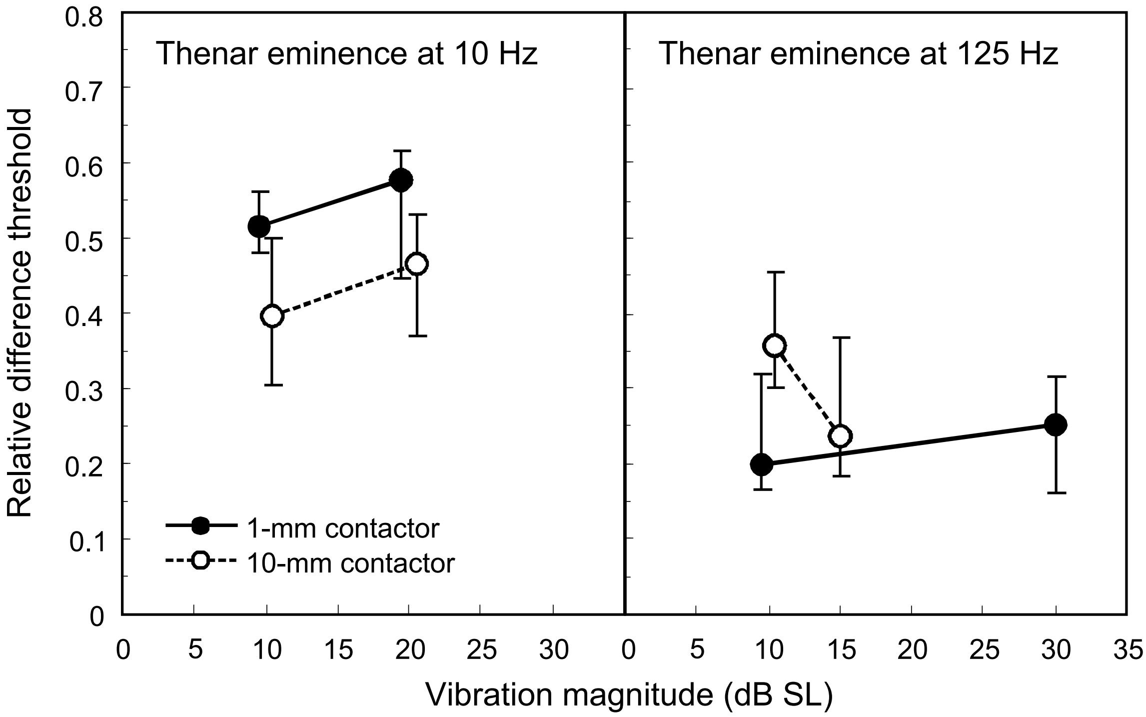

Figure 4 Effect of vibration magnitude (in dB SL) on the relative difference thresholds for 10 Hz and 125 Hz at the thenar eminence. Medians of 12 subjects and inter-quartile ranges are shown. ● 1-mm diameter contactor; o 10-mm contactor.

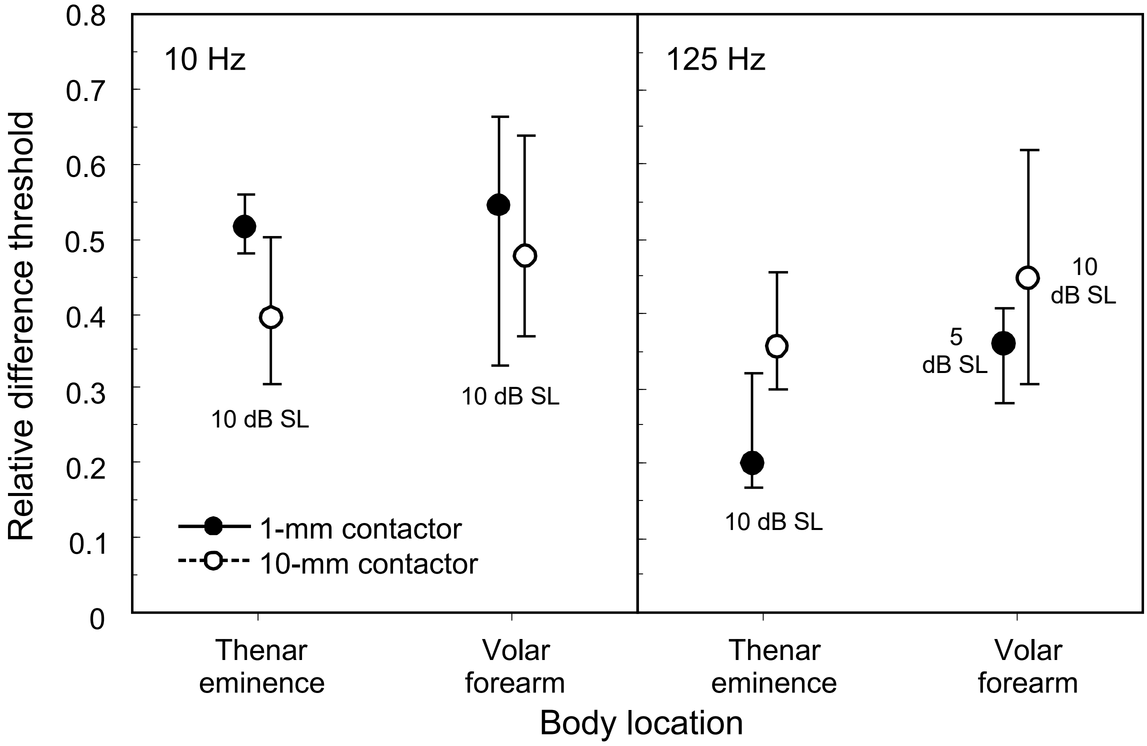

Figure 5 Effect of body location (thenar eminence and the volar forearm) on the relative difference threshold at 10 Hz and 125 Hz. Medians of 12 subjects and inter-quartile ranges are shown. ● 1-mm diameter contactor; o 10-mm contactor.