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TITLE PAGE

Thresholds for the Perception of Hand-transmitted Vibration: Dependence on Contact Area and Contact Location

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Absolute perception thresholds for hand-transmitted vibration

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Authors:
Miyuki Morioka and Michael J. Griffin

Human Factors Research Unit
Institute of Sound and Vibration Research
University of Southampton
Southampton, SO17 1BJ
England

Tel: +44 (0)23 80 592277
Fax: +44 (0)23 80 592927
Email: M.Morioka@soton.ac.uk (correspond to the first author)

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ABSTRACT

The detection of vibration applied to the glabrous skin of the hand varies with contact conditions. Three experiments have been conducted to relate variations in the perception of hand-transmitted vibration to previously reported properties of tactile channels. The effects of a surround around the area of contact, the size of the area of contact, the location of the area of contact, the contact force, and the hand posture on perception of thresholds were determined for 8 to 500 Hz vibration. Removal of a surround around a contact area on the fingertip elevated thresholds of the NP II channel (FA I fibers) at frequencies less than 31.5 Hz and reduced thresholds of the Pacinian channel (FA II fibers) at frequencies greater than about 63 Hz. When no surround was present, thresholds reduced systematically as the contact area increased from the fingertip to the whole hand at frequencies from 16 to 125 Hz, although the decrease was not inversely proportional to the increase in contact area. The results are partly explained by spatial summation in the Pacinian channel (FA II fibers) and the involvement of the NP II channel (SA II) with some influence of biodynamic responses and contact pressures. There were regional differences in sensitivity over the hand within the NP I channel but not within the Pacinian channel: the NP I thresholds (less than 31.5 Hz) decreased from proximal to distal regions of the hand, whereas the Pacinian thresholds (125 Hz) were independent of contact location over the hand.

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TEXT OF THE ARTICLE

INTRODUCTION

In occupations and in leisure activity, people experience hand-transmitted vibration from hand-held tools (e.g. hedge-trimmers, chain saws, road drills), in transport (e.g. steering wheels), and from various hand-held domestic devices (e.g. electric razors, hair driers) and domestic machinery (e.g. washing machines). Excessive exposure to hand-transmitted vibration causes vascular and neurological disorders (e.g. Bovenzi, 1990) as well as discomfort and interference with activities (Griffin, 1990). However, vibration can also provide useful tactile feedback and assist some tasks. An understanding of the characteristics of the sensory mechanisms involved in the perception of hand-transmitted vibration is required to optimize the vibration to which people are exposed.

Neurophysiological studies suggest there are four classes of mechanoreceptive afferent nerve fibers in the glabrous skin of the hand that mediate perception of vibrotactile stimuli. They are classified according to their adaptation and receptive field properties. Fast adapting (FA) fibers include Meissner corpuscles (FA I) that are most sensitive at frequencies between 5 and 50 Hz, and Pacinian corpuscles (FA II) that are most sensitive to frequencies greater than about 40 Hz. Slowly adapting (SA) fibers include Merkel discs (SA I), and Ruffini endings (SA II) that are most sensitive to frequencies less than about 8 Hz. Each class of fiber is differently distributed over the skin surface of the hand and has distinctive responses to vibration stimuli (e.g. Johansson, 1978; Johansson and Vallbo, 1979a; 1979b; 1983). The threshold curves of the four types of nerve fibers have overlapping frequency ranges: vibrotactile thresholds are thought to be determined by the nerve fibers that have the highest probability of detecting the applied stimulus.

Studies of vibrotactile perception led Bolanowski, Gescheider, Verrillo and co-workers to the concept of a multi-channel sensory system introduced to understand the properties of the four information-processing channels in the glabrous skin (Bolanowski *et al.*, 1988; Gescheider *et al.*, 2001; Gescheider *et al.*, 2002). The detection of vibration involves four independent mechanoreceptive channels often classified as Pacinian (P) and non-Pacinian (NP) channels. It became evident that the P channel provides sensations at high frequencies (e.g. greater than 40 to 50 Hz) and summates over the stimulus duration and over the excitation area, known as 'temporal summation' and 'spatial summation', respectively (Verrillo, 1963; 1968). The NP channels have relatively flat frequency response to vibration displacement and does not exhibit spatial or temporal summation but the sensitivity increases with increasing stimulus gradients at frequencies below about 40 Hz (for reviews see Gescheider, 1976; Verrillo, 1985). It was subsequently suggested that the response at lower frequencies is mediated by FA I fibers that are associated with Meissner's corpuscles (Talbot, *et al.* 1968). In the NP channels, the NP I and the NP II channels are thought to be mediated by the FA I and SA II fibers, respectively. They have been identified in studies of adaptation (Capraro *et al*., 1979) and masking (Gescheider *et al*., 1985); these procedures elevate the threshold of one channel so as to measure the sensitivity of another channel. The NP III channel, thought to be mediated by SA I fibers, was later identified by masking (Bolanowski *et al*., 1988), leading to the four-channel model of mechanoreception. From adaptation studies, Gescheider *et al.* (2001) identified the tuning curves of the four tactile channels that mediated the perception of vibration from a large contactor (1.5 cm^2-: 1.4 cm-diameter) and a small contactor (0.008 cm^2-: 0.1 cm-diameter) applied at different frequencies to the thenar eminence. Gescheider *et al.* (2002) found that that the frequency dependence of the P, NP I and NP III channels were similar at the fingertip and at the thenar eminence, although the spatial summation characteristics of the Pacinian channel differed between these locations.

The characteristics and 'tuning curves' of the tactile channels, have been developed from studies of the perception of vibration applied via small circular probes within fixed surrounds to the glabrous skin of the hand (at the fingertip or the thenar eminence). To extend this knowledge to the prediction of the perception of vibration for hand-transmitted vibration, it requires knowledge of which tactile channels mediate sensation and how the sensitivities of the relevant channels depend on contact location and contact area and combine to produce a sensation of vibration at the hand. With no surround to constrain vibration to the area of stimulation, vibration applied at one location on the hand may be perceived at other locations, and there is a less distinct gradient between the area of stimulation and the surrounding area; it is therefore uncertain whether perception thresholds will increase or decrease as the area of excitation increases from a localized area of skin to the excitation of the whole area of the hand.

Only a few studies have investigated thresholds for the perception of vibration transmitted to the whole hand. Miwa (1967) determined absolute thresholds over the range 3 to 300 Hz for the hand pressing on a flat plate. Reynolds *et al.* (1977) determined absolute thresholds over the range 25 to 1000 Hz with the hand grasping a 1.9 cm diameter handle, with two different grip forces (8.9 N and 35.6 N), three axes of vibration, and both a palm grip and a finger grip. Brisben *et al.* (1999) used vibration parallel to the axis of a cylinder (y_h-axis of the hand gripping the cylinder) over the range 10 to 300 Hz. The displacement thresholds reported from these studies show U-shaped frequency-dependence with minimum displacement at frequencies between 150 and 250 Hz, although the sensitivity varied between the studies, possibly due to differing hand postures (gripping postures and flat palm), grip forces, push forces, and psychophysical procedures for measuring thresholds. Little is known about the sensory mechanisms responsible for the perception of vibration transmitted to the whole area of the hand or how the sensitivity of the various tactile channels is influenced by these variables.

This paper describes a series of three experiments designed to compare systematically the vibration sensitivity of the whole hand with the vibration sensitivity of the fingertip. Absolute thresholds (detection thresholds) of perception of vibration stimuli were determined with various contact conditions so as to explore the differences in sensitivity and investigate alternative explanations for these differences.

EXPERIMENT 1 Absolute threshold contours at the fingertip and the hand

The purpose of this experiment was to compare absolute thresholds for the perception of vibration at the fingertip with thresholds for the whole hand over the frequency range 8 to 500 Hz. According to understanding of spatial summation in the P channel (e.g. Verrillo, 1963; 1968) and gradient effects in the NP channels (e.g. Gescheider, 1976; Verrillo, 1985), it was hypothesized that spatial summation would result in thresholds mediated by the P channel being lower for the hand than for the fingertip, while the presence of a surround at the fingertip would result in gradients so that thresholds mediated by the NP channels would be lower at the finger than at the hand. The effect of hand posture (i.e. the hand grasping a handle or pressing on a flat plate) was also examined to test whether a change in hand posture would alter sensitivity even when the contact area and the gradient stimuli were unchanged.

Materials and methods

Subjects

Twelve male volunteers participated in the study. They were all students or office workers aged between 22 and 33 years (mean 24.6 years, standard deviation 3.0), healthy (no indication of neurological disorders), non-smokers, right handed and had not been exposed to severe hand-transmitted vibration. All three experiments reported in this paper were approved by the Human Experimentation Safety and Ethics Committee of the ISVR, University of Southampton. Informed consent to participate in the experiments was given by all subjects.

Contact conditions and apparatus

Three contact conditions were employed: the right hand pressing on a flat wooden plate (referred to as PALM), the right hand grasping a wooden handle (referred to as GRIP), and the distal phalanx of the middle finger of the right hand in contact with a small circular probe within a surround (referred to as FINGERTIP). The contact conditions are described and illustrated in Table 1.

With the PALM and GRIP conditions, vibration stimuli were delivered to the hand by a Derritron VP 4 electrodynamic vibrator. A wooden contactor (either a 200 x 150 mm flat plate or a 30 mm diameter handle) was mounted on a load cell (PCB, type 353 B43) that was firmly fixed to the vibrator. The vertical acceleration was measured using a piezoelectric accelerometer (DJ Birchall, A20/T) rigidly mounted on the wooden flat plate or the wooden base of the handle. The signals from the accelerometer were passed through a charge amplifier (Brüel and Kjær, type 2635). Visual feedback of the contact force was shown on an analogue meter. A height-adjustable armrest was supplied so as to maintain the hand and arm horizontal and level with the vibrating surface.

With the FINGERTIP condition, the distal phalanx of the right middle finger was placed over the probe of an *HVLab* Tactile Vibrometer. The vibrometer contained an electrodynamic mini-shaker (Ling V101) attached via an accelerometer (PC308 B14) to a 6 mm-diameter (0.28 cm^2) nylon probe. The probe was counter-balanced to produce a constant upward force and protruded through a 10-mm diameter hole in a flat nylon plate. Strain gauges were mounted under the plate to indicate the downward push force on the surround; a meter provided visual feedback of the force applied by the finger on the surround. The finger pushed on the surround with a force of 2 N while the probe applied an upward force of 1 N. The arm was supported on the vibrometer so that the hand and arm were horizontal.

Vertical sinusoidal vibration was generated and acquired using an *HVLab* Data Acquisition and Analysis Software (version 3.81) via a personal computer with anti-aliasing filters (TechFilter) and an analogue-to-digital and digital-to-analogue converter (PCL-818). The signals were generated at 5000 samples per second and passed through 600 Hz low-pass filters. The stimulus parameters and the psychophysical measurement procedures were computer-controlled.

TABLE 1 ABOUT HERE

Procedure

Absolute thresholds were determined with a two-interval two-alternative forced-choice (2IFC) method (Zwislocki *et al*., 1958) in conjunction with the three-down one-up adaptive tracking procedure (Wetherill and Levitt, 1965). Subjects were exposed to a series of trials, each at a different frequency. A trial consisted of two 3-second periods, one contained the vibration stimulus and the other contained no stimulus, separated by a 1-second pause; the order of presenting the two periods was randomized. A small light was illuminated during both 3-second periods. The subjects were asked to detect which of the two periods contained the vibration stimulus. The vibration stimulus increased in intensity by 2 dB (25.8% increments) after an incorrect response from a subject and decreased by 2 dB after three consecutive correct responses. The stimuli commenced at a magnitude that the subjects could easily detect, and then decreased and increased according to their responses.

The threshold measurement was terminated after six reversals: a point where the stimulus level reversed direction (i.e. at either a peak or a trough). The threshold was calculated from the mean of the last two peaks and the last two troughs, omitting the first two reversals, as suggested by Levitt (1971).

The skin temperature of the fingertips was measured at the beginning of every session using a thermocouple. Threshold measurements proceeded if the skin temperature was greater than 29° Celsius, otherwise the subjects warmed their hands until this criterion was reached. Subjects wore hearing protectors during the threshold measurements, partly to prevent them hearing the stimuli and partly to encourage them to concentrate on the task of detecting vibration stimuli. Absolute thresholds were determined at each of seven frequencies: 8, 16, 31.5, 63, 125, 250 and 500 Hz. The order of presenting the seven frequencies was randomized and the order of presenting the three contact conditions was balanced. Stimuli and methodological details are listed in Table 2.

TABLE 2 ABOUT HERE

Results and discussion

Figure 1 shows the individual and median absolute thresholds from the twelve subjects expressed in acceleration (ms^{-2} r.m.s.) for each contact condition. With the PALM and GRIP conditions, the thresholds were dependent on the frequency of vibration (Friedman, $p<0.001$), with similar U-shaped contours showing greatest sensitivity at frequencies in the range 63 to 250 Hz when the thresholds are expressed in terms of acceleration. With the FINGERTIP condition, a frequency dependence of perception thresholds was also evident (Friedman $p<0.001$), but showing a clear trend towards increased thresholds with increasing vibration frequency.

FIGURE 1 ABOUT HERE

The median absolute thresholds in the three conditions (PALM, GRIP, and FINGERTIP) are compared in terms of both acceleration and displacement in Figure 2. The root-mean-square acceleration (i.e. ms^{-2} r.m.s.) is the preferred method of quantifying human exposure to vibration as required in the relevant International Standards (i.e. ISO 5349-1, 2001; ISO 13091-1, 2001), whereas peak displacement is often used in psychophysical research. Over the three conditions, there were significant differences in absolute threshold at all frequencies (Friedman, $p<0.005$), except at 31.5 Hz (Friedman, $p=0.21$).

Between the PALM and the GRIP condition, sensitivity did not differ between the two hand postures: there was no significant difference in threshold at any frequency (Wilcoxon, $p>0.05$), except at 500 Hz where thresholds were lower in the GRIP condition than in the HAND condition (Wilcoxon, $p=0.028$). The results are reasonably consistent with the hypothesis that sensitivity is not influenced by a change of hand posture if contact area and gradients are unchanged. The lowered threshold with the GRIP condition at 500 Hz may partly be due to a difference in pressure distribution over the hand: the pressure was probably more evenly distributed over the hand with the HAND condition than in the GRIP condition where there was increased contact pressure at the distal palm where the hand rested on the handle. Increases in contact pressure have been reported to reduce thresholds mediated by the Pacinian channel (Craig and Sherrick, 1969; Lamoré and Keemink, 1988; Harada and Griffin, 1991). However, this does not explain why the Pacinian thresholds reduced with the GRIP condition only at 500 Hz.

At frequencies less than 31.5 Hz, thresholds determined in the FINGERTIP condition were significantly lower than those in the PALM and GRIP conditions (Wilcoxon, $p<0.005$). At frequencies greater than 31.5 Hz, thresholds at the FINGERTIP were significantly greater than in the PALM and GRIP conditions (Wilcoxon, $p<0.03$). The results are consistent with the hypotheses: sensitivity of the non-Pacinian channel was increased in the FINGERTIP condition due to the gradient stimuli produced by the surround around the probe, as demonstrated by Verrillo (1979) and Gescheider *et al.* (1978); sensitivity of the Pacinian channel (FA II) was increased in the HAND and GRIP conditions due to the increased area of stimulation and spatial summation in the Pacinian channel (FA II) as proposed by Verrillo (1985).

When the median thresholds were plotted in terms of displacement (Figure 2), the slope of the threshold curve was approximately -10 to -14 dB per doubling of frequency between 16 and 250 Hz for the PALM and GRIP conditions and between 63 and 250 Hz for the FINGERTIP condition. The slope of the threshold curve controlled by Pacinian receptors between 15 and 200 Hz has been suggested to be approximately -12 dB per octave when expressed in displacement (e.g., Verrillo, 1963; Gescheider, 1976; Verrillo and Gescheider, 1977; Bolanowski *et al*., 1988; Gescheider *et al*., 2001). This suggests that thresholds with the PALM and GRIP condition at frequencies greater than about 16 Hz, and thresholds for the FINGERTIP with the surround at frequencies greater than about 63 Hz, may have been mediated by the Pacinian channel.

It has been proposed that the NP I channel (FA I) responds with a slope of about -5.0 dB per octave between about 3 and 35 Hz (Bolanowski *et al*., 1988) and that the NP II channel (SA II) responds with a slope of -5.0 to -6.0 dB per octave between 15 and 250 Hz (Capraro *et al*., 1979; Gescheider *et al*., 1985; Bolanowski *et al*., 1988). In the current experiment, the slope of the threshold in the FINGERTIP condition at frequencies between 8 and 31.5 Hz was approximately -6 dB per doubling of frequency, suggesting that thresholds for the FINGERTIP at frequencies less than 31.5 Hz may have been mediated by non-Pacinian channels, possibly the NP I channel, according to the findings of Gescheider *et al.* (2002) who suggested that the NP I channel mediates detection of low frequency thresholds between 1.5 and 40 Hz applied to the fingertip. The present results do not allow any conclusion as to whether the NP I (FA I) channel or the NP II (SA II) channel, or both channels, were responsible for thresholds of hand-transmitted vibration (PALM and GRIP conditions) at frequencies less than 31.5 Hz.

FIGURE 2 ABOUT HERE

The median threshold contours determined in the present study are compared with threshold contours from other studies with similar contact conditions in Figure 3. The measurement conditions corresponding to each of the threshold contours are summarized in Table 4. It appears that the shapes of the threshold contours are similar: some differences would be expected since sensitivity to vibration is influenced by various factors, such as the psychophysical method (e.g., Verrillo, 1962; Salle and Verberk, 1984; Morioka and Griffin, 2002), contact force (Craig and Sherrick, 1969; Lamoré and Keemink, 1988; Harada and Griffin, 1991), contact area (e.g., Verrillo, 1963), use of surround around the probe (e.g., Harada and Griffin, 1991; Lamoré and Keemink, 1988).

FIGURE 3 ABOUT HERE

In this study, the differences in perception threshold between the fingertip and the whole hand over the frequency range investigated were evident and can be explained by the known characteristics of the Pacinian and non-Pacinian channels. However, the results do not allow a prediction of whether thresholds for the whole hand at low frequencies (below 31.5 Hz) would become similar to those at the fingertip if the surround at the fingertip were removed.

EXPERIMENT 2 Effect of contact area, location and surround on vibration thresholds

Experiment 2 was designed to extend the knowledge obtained from Experiment 1 by examining the effect of the surround, contact area, contact location and contact force on absolute thresholds of perception from the fingertip to the whole area of the hand. It was hoped that the manner in which sensitivity to vibration depends on these factors would assist the identification of the receptors responsible for detecting hand-transmitted vibration.

Method

Subjects

Twelve male volunteers aged between 22 and 27 years (mean 24.3 years, standard deviation 2.19) participated in the experiment. All subjects were students or office workers with no history of occupational exposure to hand-transmitted vibration. They were all healthy, non-smokers, right handed and free from neurological disorders. The hand and finger dimensions of the subjects were measured using a pair of vernier calipers. For one of the subjects the contact area between the hand and the vibrating surface was measured using fingerprints and handprints in each condition. The contact areas for the other twelve subjects were estimated from their hand and finger dimensions.

Contact conditions and apparatus

Vibration perception thresholds at four frequencies (16, 31.5, 63 and 125 Hz) were measured on the glabrous skin of the right hand in eight contact conditions, as illustrated in Table 3. The contact force was fixed for each condition (1 N for the fingertip and 5 N for the finger and the whole hand conditions); contact pressure, which depends on hand size, was not controlled. For each of the 12 subjects, contact pressures were estimated from the hand and finger dimensions.

Vibration stimuli were delivered to the finger and hand using an *HVLab* Tactile Vibrometer (for Conditions A and B) and a Derritron VP4 electrodynamic vibrator (for Conditions C, D, E, F, G and H). The apparatus was the same as employed in Experiment 1. To provide a ‘no surround’ condition in Condition B, the cover of the Tactile Vibrometer was replaced with a specially designed cover with a circular hole 60 mm in diameter around the probe. There was no contact between the measured middle finger and the edge of the circular hole. Conditions B and C allowed the comparison of thresholds using two different devices with the same contact conditions: it was expected that thresholds would not differ between the two conditions. For conditions C, D, E, F, and G, contactors were mounted on the flat wooden flat plate used in Condition H.

Procedure

The procedure and the experimental environment for measuring absolute thresholds was the same as in Experiment 1 (Table 2). The only difference was the duration of the stimuli: a trial consisted of two intervals, each lasting 1.0 second, separated by a 1.0 second pause. This was not expected to influence thresholds as it was demonstrated by Gescheider *et al.* (1978) that temporal summation of the P channel is only likely to affect thresholds at durations less than 1.0 second.

Results and discussion

There were no systematic correlations between any of the absolute thresholds and skin temperature, age or body size, including the hand and finger sizes of the subjects.

Effect of surround

Figure 4 (top left graph) shows median acceleration thresholds for twelve subjects at the distal phalanx of the middle finger with and without the 10 mm diameter surround. When the surround was present, the thresholds decreased by 16.9 dB (a factor of 7) at 16 Hz and by 10.1 dB (a factor of 3) at 31.5 Hz, whereas the thresholds increased by 5.6 dB (a factor of

2.3) at 125 Hz. This threshold shifts caused by the removal of the surround was statistically significant (*p*<0.01, Wilcoxon), except at 63 Hz (*p*=0.814, Wilcoxon).

The effects of the surround are consistent with those seen in other studies and may be explained by the involvement of the Pacinian and the non-Pacinian channels. Gescheider *et al.* (1978) examined the effect of surround at the thenar eminence (using 0.2 cm^2 and 3.0 cm^2 contactor areas, 1.0 mm gap) and found decreased high frequency thresholds (above about 30-50 Hz) on removal of the surround and decreased low frequency thresholds (below about 30-50 Hz) in the presence of the surround. It was suggested that the removal of the surround allowed spreading of the vibration over the skin, equivalent to increasing the contact area. Verrillo (1979) found that sensitivity in the non-Pacinian channels (determined at 25 Hz) decreased by approximately 3.0 dB per doubling of the gap between a probe and a surround. He later concluded that the non-Pacinian channels are most sensitive to changes in gradients on the surface of the skin (Verrillo, 1985). The present results suggest that the removal of the surround enhances mediation by the Pacinian channel at frequencies greater than about 63 Hz, while the presence of the surround enhances mediation by the non-Pacinian channels at frequencies less than about 31.5 Hz.

The shapes of the threshold contours with and without a surround (i.e., Conditions A and B) are similar to those from other studies examining the effect of a surround at the fingertip (Goble *et al.*, 1996; Harada and Griffin, 1991; Lamoré and Keemink, 1988) and the thenar eminence (Gescheider *et al.*, 1978; van Doren, 1990) and are compared in Figure 5 (the conditions used in these studies are listed in Table 4). Differences in threshold contours between the studies can partly be explained by the use of different conditions. For example, thresholds determined by Gescheider *et al.* (1978) were higher than those determined with Conditions A and B in this experiment, possibly due to the use of a smaller contactor (5 mm diameter, 0.2 cm^2) relative to the one used in the present study (6-mm diameter, 0.28 cm^2). However, thresholds presented by Van Doren (1990) were also higher than those determined with Conditions A and B although a larger contactor (9.5 mm diameter, 0.71 cm^2) was employed, possibly due to the use of a shorter stimulus duration (236 ms) compared to

1 second in the present study. It is known from Gescheider *et al*. (1978) that temporal summation of the Pacinian channel affects thresholds below about 500 ms.

Thresholds at the fingertip obtained without a surround in Conditions B and C were not significantly different (p>0.1, Wilcoxon), implying that thresholds were not influenced by the use of different vibration devices.

FIGURE 4 ABOUT HERE

FIGURE 5 ABOUT HERE

Effect of contact force

As seen in Figure 4 (top right graph), thresholds at the finger determined with a 5 N contact force (Condition E) were generally higher than those determined with a 1 N contact force (Condition D). Increasing the contact force by a factor of 5 raised thresholds by 1.1, 0.5, 3.9 and 4.4 dB (ratios of 1.14, 1.06, 1.56 and 1.66) at 16, 31.5, 63 and 125 Hz, respectively, although the difference in thresholds was only statistically significant at 125 Hz (Wilcoxon, p=0.012).

The increase in thresholds with an increase in contact force at 125 Hz, where the stimuli are thought to be mediated by the Pacinian system, is not consistent with the findings of some other studies: Harada and Griffin (1991) found a reduction in thresholds with increased contact force (1, 2 and 3 N) at frequencies greater than 125 Hz when using a 10 mm diameter surround around a 7 mm diameter (0.38 cm^2) contactor at the fingertip; Craig and Sherrick (1969) found that doubling the contact force increased the sensation magnitude by approximately 3 dB when using a 0.157 cm^2 contactor and a contact force varying from 0.025 to 0.8 N applied over the volar forearm, where there are thought to be no FA I fibers (Vallbo *et al*. 1995).

Lamoré and Keemink (1988) found a strong dependence of thresholds on contact force (from 0.1 to 1.2 N) at 210 Hz at the first phalanx of the middle finger and at the thenar eminence with a 1.5 cm^2 contactor (both with and without a surround). They found maximum sensitivity with 0.7 N static force, corresponding to a contact pressure of 0.47 N/cm^2. The contact forces in Conditions D and E were 1 N and 5 N, corresponding to contact pressures of about 0.38 N/cm^2 and 1.9 N/cm^2, respectively. While the 1 N force may have been close to optimum, the 5 N force may have been greater than optimum for mediation via the Pacinian channel, resulting in elevated thresholds. However, the increased thresholds with increasing contact force at 125 Hz are not fully explained by the limited knowledge currently available.

Effect of contact area

When varying the contact area at the fingertip (bottom left graph of Figure 4), thresholds determined with a 35-mm diameter (average contact area of 2.11 cm^2) contactor (Condition D) differed from those with the-6 mm diameter (0.28 cm^2) probe (Condition C). An increase in contact area, by about a factor of 7.5, raised thresholds by 1 dB (ratio of 1.12) at 16 Hz and by 0.6 dB (ratio of 1.07) at 31.5 Hz, but decreased thresholds by 2.2 dB (ratio of 0.78) at 63 Hz and 2.7 dB (ratio of 0.72) at 125 Hz. These differences in thresholds were only statistically significant at 125 Hz (Wilcoxon, p=0.019). According to Verrillo (1963), a threshold decrease of 3 dB per doubling of contact area would be expected for Pacinian thresholds. If this theory can be applied to the present results, it would have resulted in Pacinian thresholds for the whole fingertip (Condition D) being about 8 dB (ratio of 0.4) lower than thresholds at the fingertip with the 6-mm diameter (0.28 cm^2) contactor (Condition C). The less-than-expected spatial summation observed in the present study may be partially explained by the effect of static force: in this experiment a constant contact force of 1 N was applied while increasing the contact area (from Condition C to Condition D), whereas Verrillo (1963) maintained a constant contactor penetration of 1 mm when changing contact area. Craig and Sherrick (1969) examined the effect of spatial summation on thresholds while maintaining either a fixed contact force, a fixed contact penetration, or a fixed contact pressure, and found that the spatial summation effect was stronger with constant contact pressure than with constant contact penetration. The spatial summation was also stronger with constant contact penetration than with constant contact force. An increase in static penetration can decrease thresholds (Makous *et al*., 1996). With increased contact area, the constant contact force used in the current experiment will have produced less contact pressure and reduced contact penetration, counteracting the effect of spatial summation.

When increasing the contact area from the fingertip to the whole hand (Conditions E, F, G and H), thresholds generally decreased with increasing area at all frequencies (Friedman, $p<0.001$), as seen in Figure 4 (bottom right graph). There were statistically significant decreases in thresholds when increasing the contact area from the fingertip to the whole finger (Condition E to Condition F: $p<0.001$, except at 63 Hz, p=0.14; Wilcoxon). On increasing the contact area to the whole hand (Condition G to Condition H), there was a further decrease in thresholds at 31.5 and 63 Hz ($p<0.05$, Wilcoxon), but not at 125 Hz. Unexpectedly, 10 of the 12 subjects showed no change, or a reduced sensitivity, at 125 Hz when the contact area increased further from Condition G to Condition H ($p=0.0076$, Wilcoxon), as seen in Figure 4 (bottom right graph). There were no significant differences in thresholds at 16 Hz between Conditions F, G and H (Friedman, $p=0.17$).

It appears that spatial summation was present over the whole hand not only at high frequencies (i.e. 63 and 125 Hz), but also at low frequencies (i.e. 16 and 31.5 Hz). Figure 6 shows the changes in vibration perception thresholds as a function of both the contact area and the contact location on the hand. Unlike the spatial summation effect applied at the thenar eminence by Verrillo (1963), a proportional decrease in threshold with increasing contact area is not seen in the present results. The contact area increased by a factor of 2.6 when the contact location extended from the fingertip (Condition E) to the whole finger (Condition F), while the thresholds decreased by 7.4, 10.3, 3.4 and 5.1 dB (ratio of 0.43, 0.31, 0.68 and 0.56) at 16, 31.5, 63 and 125 Hz, respectively. The contact area increased by a similar amount (a factor of 2.2) when the contact location was extended from the four fingers (Condition G) to the whole hand (Condition H), and the thresholds decreased by only 1.3, 4.9, and 3.8 dB (ratio of 0.86, 0.57 and 0.65) at 16, 31.5 and 63 Hz, respectively, and thresholds increased by 1.0 dB (ratio of 1.12) at 125 Hz.

Extending the contact area from the fingertip to the hand greatly changed the location of stimulation. Spatial summation of vibration perception may be influenced by the part of the hand in contact with the vibrating surface, with lower thresholds in areas of the hand where the receptors have greater sensitivity. Increasing the contact area to the whole of the hand would be expected to increase the chances of exciting any nerve fibers that are exceptionally sensitive to vibration. Pronounced frequency-dependent regional differences in vibration perception have been reported over the hand (Roland and Nielsen, 1980; Löfvenberg and Johansson, 1984; Lundström, 1984), although the relevance of these findings is not clear as a surround was not used around the contactor. The absence of a surround in those experiments may have failed to produce a threshold response in the non-Pacinian channels, while allowing a spreading of vibration over the skin around the contactor that would result in spatial summation in the Pacinian channel. However, it may be concluded that an increase in the area of contact with the hand is not the only possible explanation for the increased sensitivity in the hand compared to the finger: variations in sensitivity with the location of contact with the hand could also contribute to a difference it in thresholds.

FIGURE 6 ABOUT HERE

EXPERIMENT 3 Effect of contact location in the glabrous area of the hand

Experiment 2 found a decrease in thresholds as the area of contact with excitation increased from the fingertip to the whole hand. A possible explanation is that thresholds were lower with the larger contact area because there was a greater sensitivity at some locations in the hand: the larger contact areas were more likely to include the locations where exceptionally sensitive nerve fibers are activated, resulting in lower thresholds with increased contact area.

Experiment 3 was designed to examine how the sensitivity of Pacinian and non-Pacinian channels vary with location over the glabrous skin of the hand.

Method

Subjects

Twelve male volunteers, aged 23 to 32 years (mean 25.9 years, standard deviation 3.23), participated in the experiment. All subjects were students or office workers with no history of occupational exposure to hand-transmitted vibration. They were all healthy, non-smokers, right handed and free from neurological disorders.

Contact conditions and apparatus

Vibration perception thresholds were determined for eight locations on the glabrous skin of the right hand at four frequencies (16, 31.5, 63 and 125 Hz). The locations are shown in Figure 7. Three contact locations were defined: distal part of the finger (referred to as DISTAL FINGER: test points 1, 2 and 3), distal part of the palm (referred to as DISTAL PALM: test points 4, 5 and 6), and proximal part of the palm (referred to as PROXIMAL PALM: test points 7 and 8).

An *HVLab* Tactile Vibrometer with a 6-mm diameter (0.28 cm^2) contactor and a 10-mm diameter surround was employed to determine vibrotactile thresholds: the same equipment and similar contact conditions used for the FINGERTIP condition in Experiment 1 and Conditions A in Experiment 2. In this experiment, the upward contact force from the contact probe was 0.5 N and the downward push force on the surround was 2.0 N.

FIGURE 7 ABOUT HERE

Procedure

The up-and-down method of limits (von Békésy tracking method) was used to determine perception thresholds. The magnitude of vibration was increased and decreased with continuous stimuli at a constant rate (5 dB/s until the first response, subsequently at 3 dB/s). A subject responded by pressing a button whenever he perceived the vibration stimulus. The direction of change of stimulus magnitude was reversed according to the response of the subject: the magnitude of the stimulus decreased until the subject no longer perceived vibration and then increased until the subject began to perceive vibration. A measurement was terminated after 30 seconds. A threshold was calculated as the mean of the mean peak and the mean trough, ignoring the first cycle of the measurement. The experimental method employed for threshold measurements is summarized in Table 2. All threshold determinations were performed in one session with the order of presentation balanced according to a Latin-square for test locations and randomized for test frequencies. Test points were marked on the hand using a pen so that they could be repeated at the same location.

Results and discussion

Median threshold contours for the test points within the DISTAL FINGER, the DISTAL PALM, and the PROXIMAL PALM, expressed in terms of acceleration and displacement, are shown in Figure 8. For each frequency, there were no differences in threshold between the three points within the DISTAL FINGER (i.e. between test points 1, 2 and 3; Friedman, $p>0.2$), between the three points on the DISTAL PALM (i.e. test points 4, 5 and 6; Friedman, $p>0.15$), or between the two points at the PROXIMAL PALM (i.e. test points 7 and 8; Wilcoxon, $p>0.4$, except for 16 Hz, $p=0.008$).

FIGURE 8 ABOUT HERE

Median perception thresholds are compared for each frequency across the eight test locations in Figure 9. The DISTAL FINGER (i.e. test points 1, 2, and 3) was the most sensitive to vibration at frequencies less than 63 Hz. The thresholds at the DISTAL FINGER (average of thresholds at test points 1, 2, and 3) were significantly lower than those at the DISTAL PALM (average of thresholds at test points 4, 5, and 6) at 16 and 31.5 Hz (Wilcoxon, $p<0.01$), differing in threshold by 5.9 and 3.7 dB (ratio of 1.98 and 1.54) at 16 and 31.5 Hz, respectively. Thresholds at the DISTAL FINGER (average of thresholds at test points 1, 2, and 3) were significantly lower than those at the PROXIMAL PALM (average of thresholds at test points 7 and 8) at frequencies less than 63 Hz (Wilcoxon, $p<0.05$), differing in threshold by 3.8, 3.1, and 3.0 dB at 16, 31.5, and 63 Hz, respectively. There were no significant differences in threshold between the DISTAL PALM and the PROXIMAL PALM at frequencies less than 63 Hz (Wilcoxon, $p>0.9$). The FA I nerve fibers (Meissner corpuscles) are most sensitive to vibration at frequencies between about 8 and 64 Hz, whereas the FA II fibers (Pacinian corpuscles) are most sensitive to vibration above about 64 Hz (Johanson *et al.* 1982). According to the 'gradient theory', the response to vibration at low frequencies (i.e. below 30 to 40 Hz) is dominated by a non-Pacinian channels when there is a surround: a gap between a probe and a surround provides a stimulus gradient to elicit the non-Pacinian response. This influence of a surround has been found in several studies (e.g. Gescheider *et al*., 1978; Goble *et al*., 1996; Harada and Griffin, 1991; Lamoré and Keemink, 1988; Van Doren, 1990) when using stimuli applied at the fingertip or the thenar eminence; it was also seen in the present results of Experiment 2. Since a surround was present in the current experiment, the perception thresholds at 16 and 31.5 Hz (and possibly 63 Hz) are likely to have been mediated by the FA I fibers. The results are partly consistent with a similar study in which vibrotactile perception thresholds were measured at seven points on the glabrous skin of the hand with a 6 mm diameter (0.28 cm^2) probe without a surround (Löfvenberg and Johansson, 1984). They found most sensitivity at distal locations on the finger and less sensitivity at proximal locations on the finger or palm of the hand at low frequencies (less than 40 to 60 Hz) and suggested that thresholds were related to the density of the receptors. The FA II fibers are evenly distributed over the glabrous skin of the hand, whereas the FA I fibers are more dense at the fingertips and less dense at the palm (Johansson and Vallbo, 1979b). In the present results, thresholds decreased as the contact location moved from proximal to distal regions of the hand at 16, 31.5 and 63 Hz, suggesting that sensitivity to vibration in the glabrous skin of the hand reflected the increased density of the FA I fibers in distal areas. However, it is not certain that the low frequency stimuli used by Löfvenberg and Johansson (1984) would have elicited responses of the FA I fibers, since the absence of a surround would have reduced the sensitivity of FA I fibers in their study.

At 125 Hz, regional variations in threshold showed a different trend compared to those at lower frequencies. Thresholds at 125 Hz did not differ between the DISTAL FINGER and the DISTAL PALM (Wilcoxon, $p>0.1$) except between test points 3 and 4 (Wilcoxon, $p=0.034$), and thresholds of the DISTAL PALM were significantly lower than those at the PROXIMAL PALM (Wilcoxon, $p<0.03$). The changed pattern of regional differences in thresholds at 125 Hz compared with those at frequencies less than 63 Hz suggests that different mechanoreceptive nerve fibers were mediated, such as FA II fibers for perception thresholds at 125 Hz and FA I fibers at lower frequencies. The present results are generally consistent with other studies and the theory of Löfvenberg and Johansson (1984) that the higher the density the lower the psychophysical thresholds; the lowest thresholds at frequencies less than 63 Hz were obtained at the DISTAL FINGER where the density of FA I fibers is highest, and less variation in thresholds over the hand at 125 Hz where the FA II fibers are evenly distributed. Löfvenberg and Johansson (1984) found less variation in thresholds across seven test points in the hand at high frequencies, above 40 to 60 Hz, than at low frequencies. Roland and Nielsen (1980) determined 100 Hz thresholds over eight test points in the glabrous area of the hand in normal and patient populations using a 13 mm-diameter (1.32 cm^2) probe (with no surround) and found no significant differences in thresholds between the test points, with the exception of the fifth digit. Lundström (1984) measured vibrotactile thresholds at fifteen points on the glabrous part of the hand within the frequency range 25 to 1000 Hz using a 9 mm-diameter (0.64 cm^2) probe (with no surround) and found small differences in sensitivity between locations. All these authors suggested the involvement of the FA II fibers (Pacinian corpuscles) in responses to vibration at high frequencies. The discrepancy between the results of apparently similar studies supports the finding of Gescheider *et al.* (2002) who compared 300 Hz Pacinian thresholds at locations between the fingertip and the thenar eminence with various sizes of contactor (i.e. 0.025, 0.1, 0.38 and 0.75 cm^2). They found that thresholds were lower at the fingertip than the thenar eminence only when the contactor was smaller than 0.75 cm^2. This is consistent with thresholds from Roland and Nielsen (1980) and Lundström (1984) which show no variation in thresholds over the glabrous skin of the hand when using relatively large contactors, 1.32

cm^2 and 0.64 cm^2, respectively. Moreover, the range of frequencies mediated by the FA II fibers will depend on the probe size and the presence or absence of a surround: an increased sensitivity of the Pacinian channel is likely with an increased contact area (spatial summation), and a decreased sensitivity of the NP I channel is likely when the surround is removed; both changes (increased area and absence of a surround) will tend to extend the low frequency range mediated by the FA II fibers.

There were few correlations between vibrotactile thresholds and skin temperature, age, body size or the relative hand and finger sizes, and no systematic correlations were found.

FIGURE 9 ABOUT HERE

GENERAL DISCUSSION

An increased sensitivity to vibration stimuli with increasing contact area was evident. In Experiment 2, at all frequencies investigated (i.e. 16, 31.5, 63 and 125 Hz), perception thresholds for the hand were more than 10 dB lower than those for the fingertip (without a surround around the probe). This suggests that spatial summation in the Pacinian channel enhanced the detection of hand-transmitted vibration. As suggested in Experiment 1, thresholds for the hand at frequencies greater than about 16 Hz were probably mediated by the Pacinian channel because of the similarity to the slope of the displacement threshold curve (-12 dB per octave) found in other studies (Verrillo, 1963; Gescheider, 1976; Verrillo and Gescheider, 1977; Bolanowski *et al*., 1988; Gescheider *et al*., 2001).

The proportional decrease in threshold with increasing contact area (3 dB decrease in threshold per doubling of contact area) reported by Verrillo (1963) was not seen in the results of Experiment 2. The present findings were similar to the results obtained by Brisben *et al*. (1999) who determined perception thresholds at 40 Hz and 300 Hz using a 32 mm diameter cylinder with various contact conditions (i.e. contact with one or two digits at the distal, middle and proximal fingers, and distal or middle part of the palm grasped by the whole hand). Thresholds determined by Brisben *et al*. (1999) were not proportional to the contact area but were dependent on contact location: the closer to the palm, the lower the threshold, even when the contact area was little changed. This suggests that Pacinian thresholds depend on contact location, with reduced thresholds when vibration excites areas where the nerve fibers have high sensitivity. The results of Experiment 3 show regional differences in thresholds in the non-Pacinian channels but not in the Pacinian channel, indicating that the sensitivity of the non-Pacinian channels increases from proximal to distal regions where the density of the FA I nerve fibers increases in the same manner. Since the Pacinian corpuscles (FA II) are evenly distributed in the glabrous area of the skin (Johansson and Vallbo, 1979b), this theory (regional differences in sensitivity of the Pacinian channel) must be rejected.

An alternative explanation for the non-proportional spatial summation to contact area in the present results would be changes in the propagation of vibration stimuli associated with changes in the contact location (i.e. from the fingertip to whole hand). Vibration applied to the skin by a vibrating surface can spread around the vicinity of the area of contact if there is no constriction (e.g. a surround). This would excite nerve fibers innervating an area of the skin larger than the area of vibrating surface. Spatial summation via the Pacinian channel has been modeled by Gescheider *et al*. (1999) in terms of neural integration and probability summation. The term 'neural integration' implies an increasing number of active fibers with increased contact area, resulting in a decrease in the threshold with increased contact area. The term 'probability summation' implies that the probability of exciting the most sensitive fibers increases with increased contact area, also resulting in a decrease in the threshold with increased contact area. Reduced spatial summation on the fingertip compared to the thenar eminence was interpreted by Gescheider *et al*. (2002) in terms of two components of spatial summation: neural integration and probability summation. Assuming neural integration or probability summation apply to the perception of some frequencies of hand-transmitted vibration, absolute thresholds of perception will be primarily influenced by the area of the hand excited by vibration not the area in contact with the vibrating surface.

The transmission of vibration within the finger and hand will also depend on vibration frequency. This will result in a frequency-dependent effect of contact location if there is either spatial summation or differences in sensitivity with location. Several studies have reported a frequency-dependence in the transmission of vibration, with frequencies greater than 100 Hz tending to be more localized to areas of the hand and fingers directly in contact with a vibrating surface, and frequencies less than 100 Hz transmitted to a wider area of the hand (e.g. Reynolds and Angevine, 1977; Sörensson and Burström, 1997). It can be expected that greater transmission of vibration will result in a greater number of nerve fibers being activated, which will result in reduced thresholds. Decreased thresholds at frequencies less than 63 Hz with increasing contact area from the fingertip to the whole area of the hand seen in Experiment 2 may partly be influenced by increased transmission of vibration. A resonance of the hand-arm-system in the region of 30 Hz seems possible for the contact conditions employed (Reynolds and Angevine, 1977; Mishoe and Suggs; 1977; Sörensson and Burström, 1997). Vibration at 31.5 Hz may have been amplified by a resonance of the hand and arm when the whole area of the hand was in contact with a vibrating surface, resulting in a lowering of the thresholds at this frequency. However, all the biodynamic studies have employed much higher magnitudes of vibration than used in the present experiments (i.e. well above the perception threshold). In addition, the transmission of vibration is influenced by grip force and is expected to increase with increasing contact pressure (Burström, 1990; Hartung *et al.*, 1993; Reynolds and Angevine, 1977). In Experiment 2, a constant contact force was applied while increasing contact area, resulting in a decrease in contact pressure with increasing contact area. It is therefore suggested that a constant contact force (reduced contact pressure with increased contact area) employed in Experiment 2 did not enhance the spatial summation effect.

The results of present experiments do not identify the tactile channels within the non-Pacinian channels responsible for perception, but it can be expected that in addition to the P and NP I channel, the NP II channel may be involved in the detection of hand-transmitted vibration. As reported by (Bolanowski *et al.* 1988), it is not known if the NP II channel exhibits spatial summation. It is possible that when stimulation was applied over the whole hand there was increased sensitivity of the NP II channel compared to when stimulation was applied to a smaller area, such as the fingertip. Morioka and Griffin (accepted for publication) determined masked thresholds for vibration applied to the fingertip and the whole hand: they masked the response of one tactile channel so as to detect responses of other channels and found some involvement of the NP II channel (FA II fibers) in the determination of perception thresholds at frequencies between 31.5 and 63 Hz. It has been suggested that the SA II fibers play a role in regulating force coordination of the hand (Westling and Johansson, 1987); they found most SA II fibers were excited by skin deformation or stretch caused by grip forces and load forces while grasping objects. The previous research suggests that the force regulated by the whole hand in contact with a vibrating surface may be enough to excite SA II fibers when the whole hand is in contact with a vibrating surface. Further investigations are required to confirm how the individual tactile channels contribute to the perception of hand-transmitted vibration at threshold and supra-threshold levels.

CONCLUSIONS

Removal of a 10-mm diameter surround around a 6-mm diameter (0.28 cm^2) probe applied at the fingertip elevated vibrotactile thresholds at frequencies less than 31.5 Hz but reduced thresholds at 125 Hz. It is concluded that the removal of the surround enhanced mediation by the Pacinian channel (FA II fibers) at frequencies greater than about 63 Hz, while the presence of the surround enhanced mediation by the non-Pacinian channels at frequencies less than 31.5 Hz. It was suggested that the thresholds determined with vibration at frequencies less than 31.5 Hz involved the NP I channel (FA I fibers), since thresholds for vibration applied by a probe with a surround at frequencies less than 31.5 Hz decreased from proximal to distal regions of the hand, consistent with the increased density of the FA I fibers in distal areas

Thresholds reduced systematically as the contact area increased from the fingertip to the whole hand, although the decrease was not inversely proportional to the increase in contact area. The presence of spatial summation suggests that thresholds for the detection of vibration applied to the whole hand at frequencies greater than about 16 Hz are likely to have be mediated by the Pacinian channel (FA II fibers). Regional differences in sensitivity within the Pacinian channel over the hand are not a likely explanation for the spatial summation not being proportional to contact area, because Pacinian thresholds (at frequencies greater than 63 Hz) were independent of contact location on the hand. The increased sensitivity with increased contact area (from finger to whole hand) may be caused by greater transmission of vibration from the hand than the finger and differences in contact pressures between hand and finger, in addition to spatial summation within the Pacinian channel. The involvement of NP II channel (SA II fibers) in the detection of vibration applied by the whole hand is considered but can only be confirmed by further research.

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TABLES

Table 1. Contact conditions and the contact source for Experiment 1.

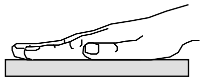
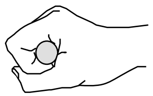
Condition	Finger or hand posture	Contact location	Dimension of contactor	Contact force	Vibration device
PALM		Whole hand (palm flat posture)	200 mm × 150 mm wooden plate	10 N	VP4
GRIP		Whole hand (gripping posture)	30 mm diameter cylindrical wooden handle	10 N	VP 4
FINGERTIP		Distal phalanx of the middle finger	6 mm diameter contactor 10 mm diameter surround	1 N	Tactile Vibrometer

Table 2. Summary of the threshold measurement method employed in each experiment.

	Experiment 1	**Experiment 2**	**Experiment 3**
Test frequency (Hz)	8, 16, 31.5, 63, 125, 250, and 500	16, 31.5, 63, and 125	16, 31.5, 63, and 125
Algorithm	Staircase (3-down 1-up rule)	Staircase (3-down 1-up rule)	von Békésy
Stimulation	Intermittent	Intermittent	Continuous
Response procedure	Two-interval forced-choice (2IFC)	Two-interval forced-choice (2IFC)	Yes-no
Intermittent stimulation			
- burst duration	3.0 s	1.0 s	-
- quiescent duration	1.0 s	> 1.0 s	
Continuous stimulation	-	-	
- maximum duration			30 seconds per test
Step rate	2 dB	2 dB	3 dB/s
Trial number	25-30 trials	20-25 trials	-
Subject response	Oral (1st or 2nd)	Oral (1st or 2nd)	Response button (press-yes, release-no)
Calculation of thresholds	Mean of last 4 reversals	Mean of last 4 reversals	Mean of reversals (> 6 reversals)

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Table 3. Contact conditions and the contact source for Experiment 2. * Average of contact area from twelve subjects.

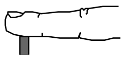
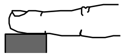
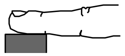
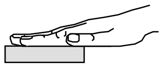
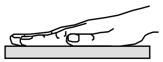
Condition	Finger or hand posture	Contact location	Dimension of contactor	Contact area	Contact force	Vibration device
A		Distal phalanx of the middle finger	6 mm diameter contactor (10 diameter surround)	0.28	1 N	Tactile Vibrometer
B		Distal phalanx of the middle finger	6 mm diameter contactor (no surround)	0.28	1 N	Tactile Vibrometer
C		Distal phalanx of the middle finger	6 mm diameter contactor (no surround)	0.28	1 N	VP 4
D		Distal phalanx of the middle finger	35 mm diameter contactor	2.23*	1 N	VP 4
E		Distal phalanx of the middle finger	35 mm diameter contactor	2.64*	5 N	VP 4
F		Whole middle finger	22 × 120 mm wooden plate	6.49*	5 N	VP 4
G		Four whole fingers (excluding the thumb)	120 × 120 mm wooden plate	20.99*	5 N	VP 4
H		Whole hand	220 × 150 mm wooden plate	44.22*	5 N	VP 4

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Table 4. Psychophysical measurement conditions corresponding to the absolute thresholds shown in Figures 3 and 5.

Year	Author(s)	Locations	Methodology	Vibration stimuli				Input conditions		Subjects		Environmental	
				Frequency range	Axis	Duration	Step rate	Contactor	Coupling force	Number (M[1], F[2])	Age	Skin temp.	Room temp.
1967	Miwa	Whole hand	*2IFC	3-300 Hz (9)	X	3 or 6 sec.	0.1 dB	Table 25×20×2.2cm	50 N push	10 (M)	Δ	Δ	Δ
1977	Reynolds *et al.*	Whole hand	Δ	25-1000 Hz (16)	X	Δ	Δ	Handle 19.05 cm ∅	8.896 N grip	8	Δ	Δ	Δ
1999	Brisben *et al.*	Whole hand	*2IFC 2D1U rule	10-300 Hz (9)	Y	1 sec. (600 ms pause)	1 dB (initial 4 dB)	Handle 32 mm ∅	No grip force	19 (11M 8F)	21-45	Δ	Δ
1963	Verrillo	Fingertip (second phalanx of third finger)	[3]MOL	25-640 Hz (7)	X	1 sec.	1 dB	12.9 mm∅ with 1 mm surround gap	1 mm indentation	4	Δ	Δ	Δ
1991	Harada and Griffin	Fingertip	Δ	16-800 Hz (18)	X	Δ	Δ	7 mm∅ with 1.5 mm surround gap	2 N	5 (M)	23-28	Above 35 °C	25 °C
2002	Gescheider *et al.*	Fingertip (index of right hand)	*2IFC 75% correct response	0.4-500 Hz (24)	X	0.7 sec.	1 dB	9.5 mm∅ with 1 mm surround gap	1 mm indentation	5 (2M 3F)	19-22	30 °C (±0.5)	Δ
1978	Gescheider *et al.*	Thenar eminence	[4]Bekesy	25 - 700 Hz	X	1 sec. (1sec. pause)	1 dB/sec	5 mm∅ with 1 mm surround gap	1 mm indentation	5	20-39	Δ	Δ
1988	Lamore and Keemink	Fingertip (distal phalanx of middle finger)	*2IFC 3D1U rule	5-1000 Hz (12)	X	1 sec. (2 sec. pause)	2 dB	13.8 mm∅ with 1 mm surround gap	0.5 N	9	Δ	35 °C	Δ
1990	VanDoren	Thenar eminence	*2IFC 75% correct response	10-250 Hz (12)	X	236 ms (1 sec pause)	1 dB	9.5 mm∅ with 1 mm surround gap	1 mm indentation	5 (3M 2F)	20-58	Δ	Δ
1991	Harada and Griffin	Fingertip	Δ	16-500 Hz (6)	X	Δ	Δ	7 mm∅ with 1.5 mm surround gap	2 N	5 (M)	23-28	Above 35 °C	25 °C
1996	Goble *et al.*	Fingertip (left index)	3IFC 3D1U rule	10-400 Hz (10)	X	500 ms (1sec pause)	1 dB (initial 3 dB)	7 mm∅ with 1 mm surround gap	0.5 mm indentation	14	18-30	31 °C	Δ

[1]M = Male [2]F = Female [3]MOL = Method of limits [4]Békésy = von Békésy method
*2IFC = Two-interval forced choice tracking method 2D1U = Two-down one-up rule 3D1U = Two-down one-up rule X = vertical Y = lateral Δ = not specified or lack of information

FIGURE LEGENDS

FIG.1. Individual absolute thresholds for twelve subjects and the median threshold contour determined with PALM, GRIP and FINGERTIP.

FIG.2. Comparison of median absolute thresholds between PALM, GRIP and FINGERTIP, expressed in acceleration (top graph) and in displacement (bottom graph).

FIG.3. Median absolute thresholds for each contact condition overlaid with previous studies.

FIG.4. Median absolute thresholds from twelve subjects: effect of surround (top left), effect of contact force (top right), effect of contact area within the fingertip (bottom left) and effect of contact area from the fingertip to the whole hand (bottom right).

FIG.5 Median absolute thresholds with and without a surround compared with the previous studies.

FIG. 6 Effect of contact area and contact location on median absolute thresholds determined with 16, 31.5, 63 and 125 Hz.

FIG. 7 Location of eight test points on the glabrous skin of the hand.

FIG. 8 Comparison of median absolute thresholds within DISTAL FINGER, DISTAL PALM, and PROXIMAL PALM, expressed in acceleration (left graphs) and in displacement (right graphs).

FIG. 9 Median absolute thresholds as a function of test point determined with 16, 31.5, 63 and 125 Hz.

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FIGURES

FIG. 1.

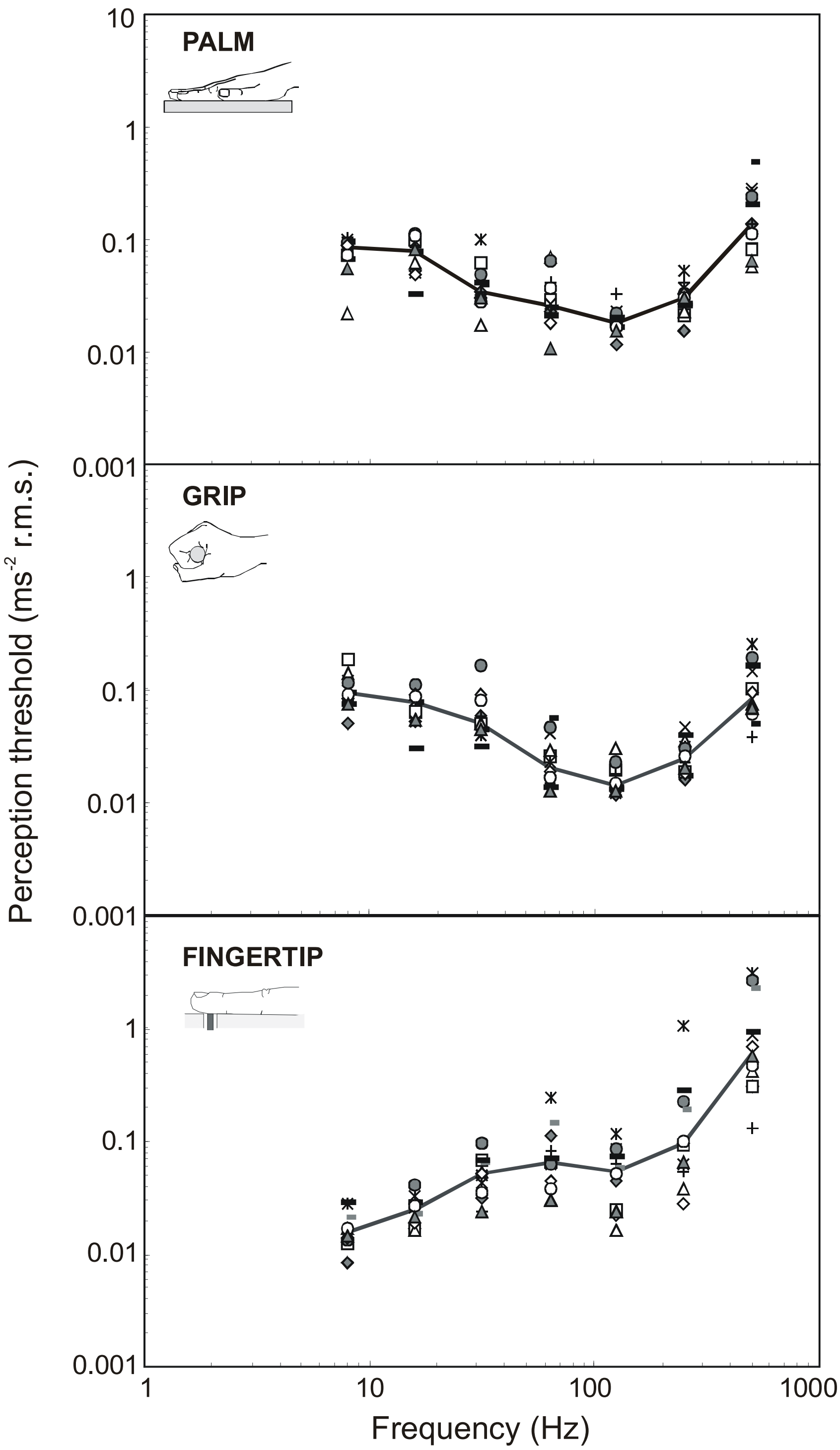

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FIG. 2.

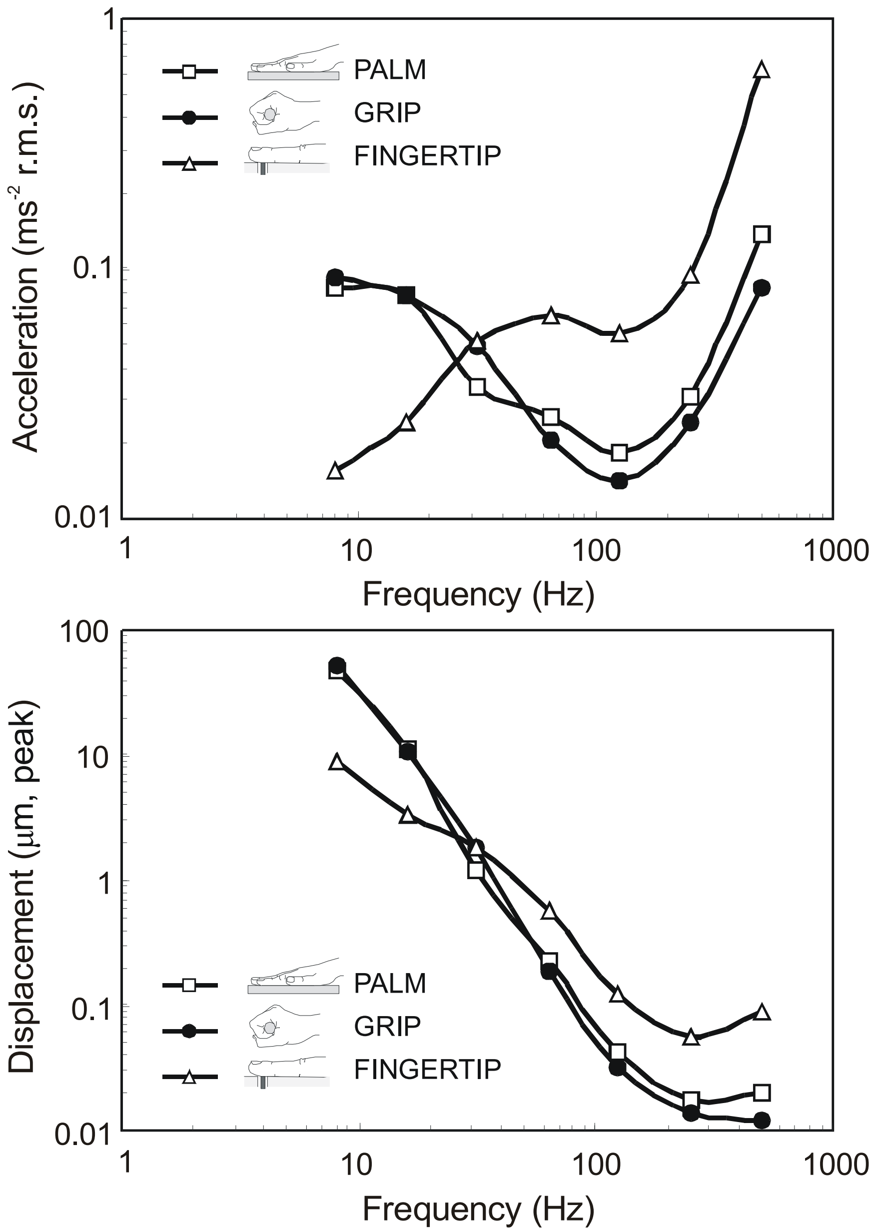

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FIG. 3

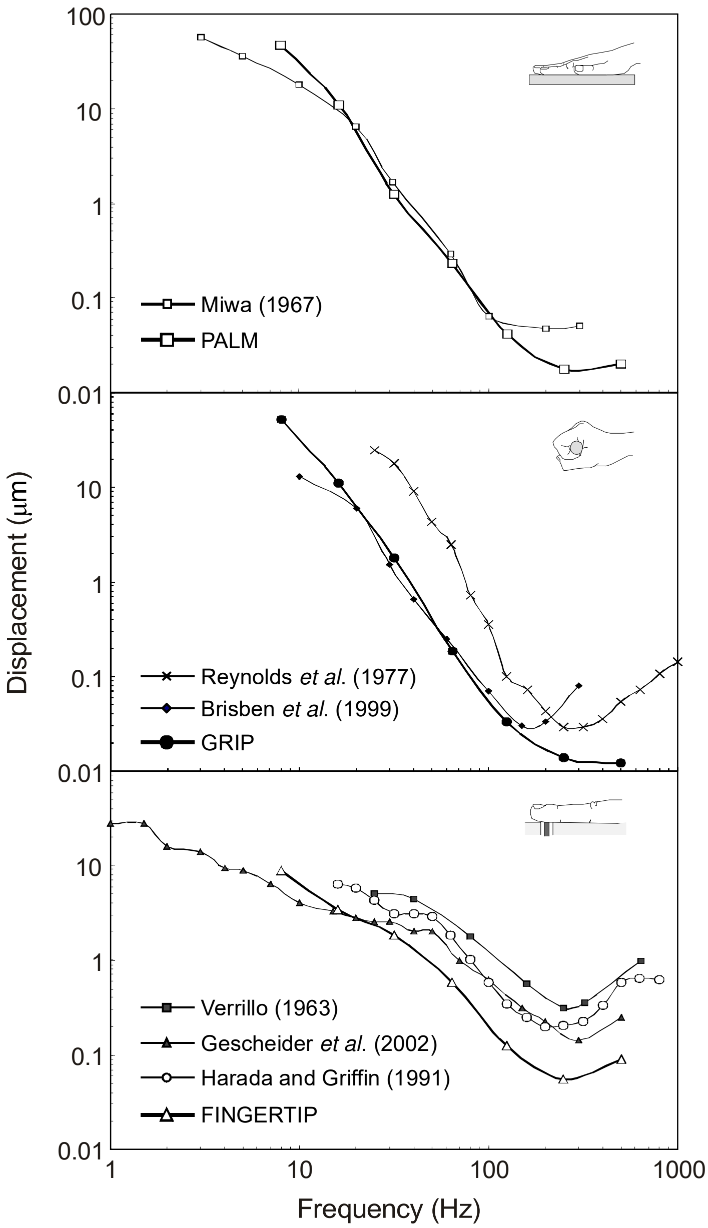

FIG. 4

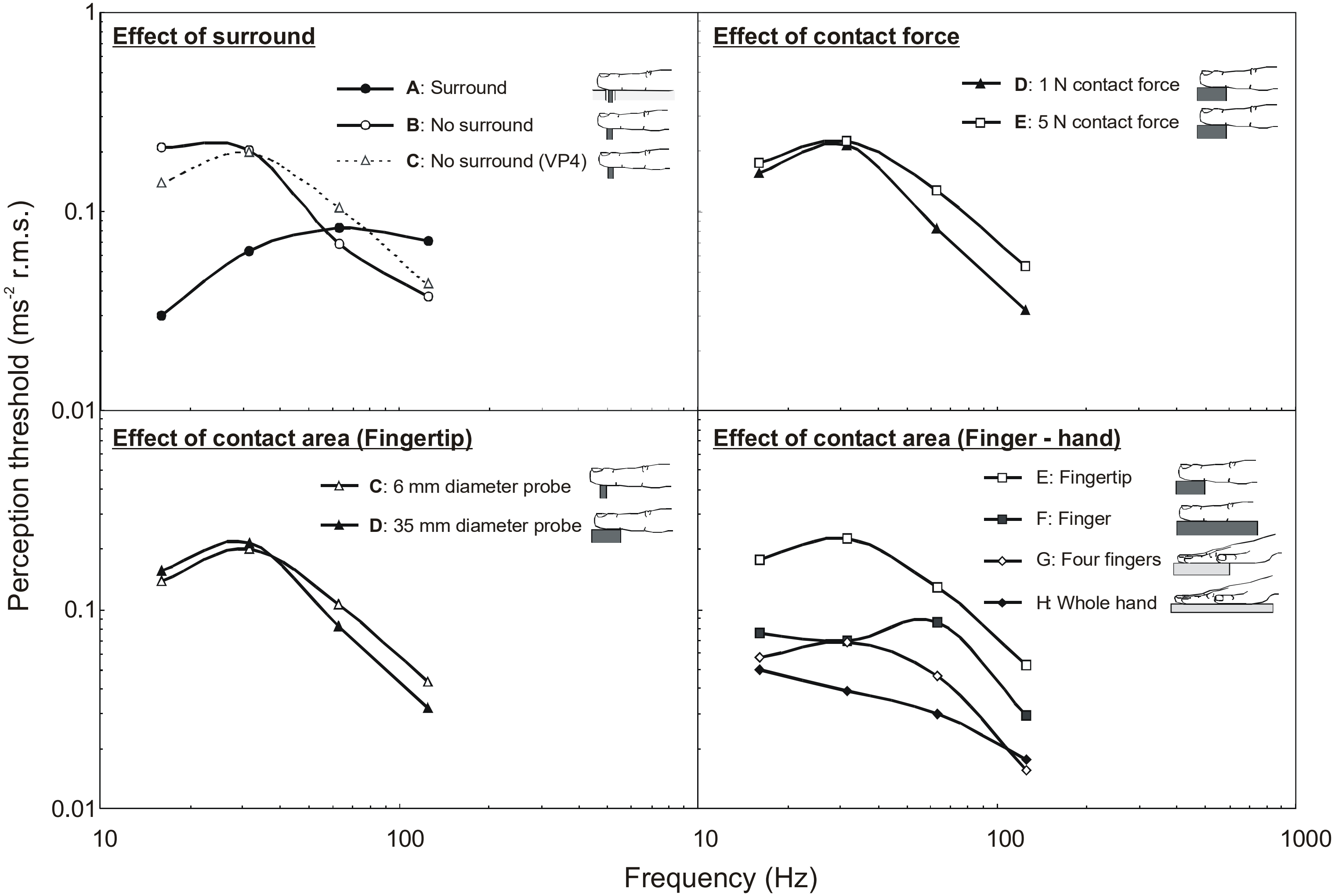
Effect of surround
A: Surround
B: No surround
C: No surround (VP4)
Effect of contact force
D: 1 N contact force
E: 5 N contact force
Effect of contact area (Fingertip)
C: 6 mm diameter probe
D: 35 mm diameter probe
Effect of contact area (Finger - hand)
E: Fingertip
F: Finger
G: Four fingers
H: Whole hand
Perception threshold (ms-2 r.m.s.)
1
0.1
0.01
10
100
1000
Frequency (Hz)

FIG. 5

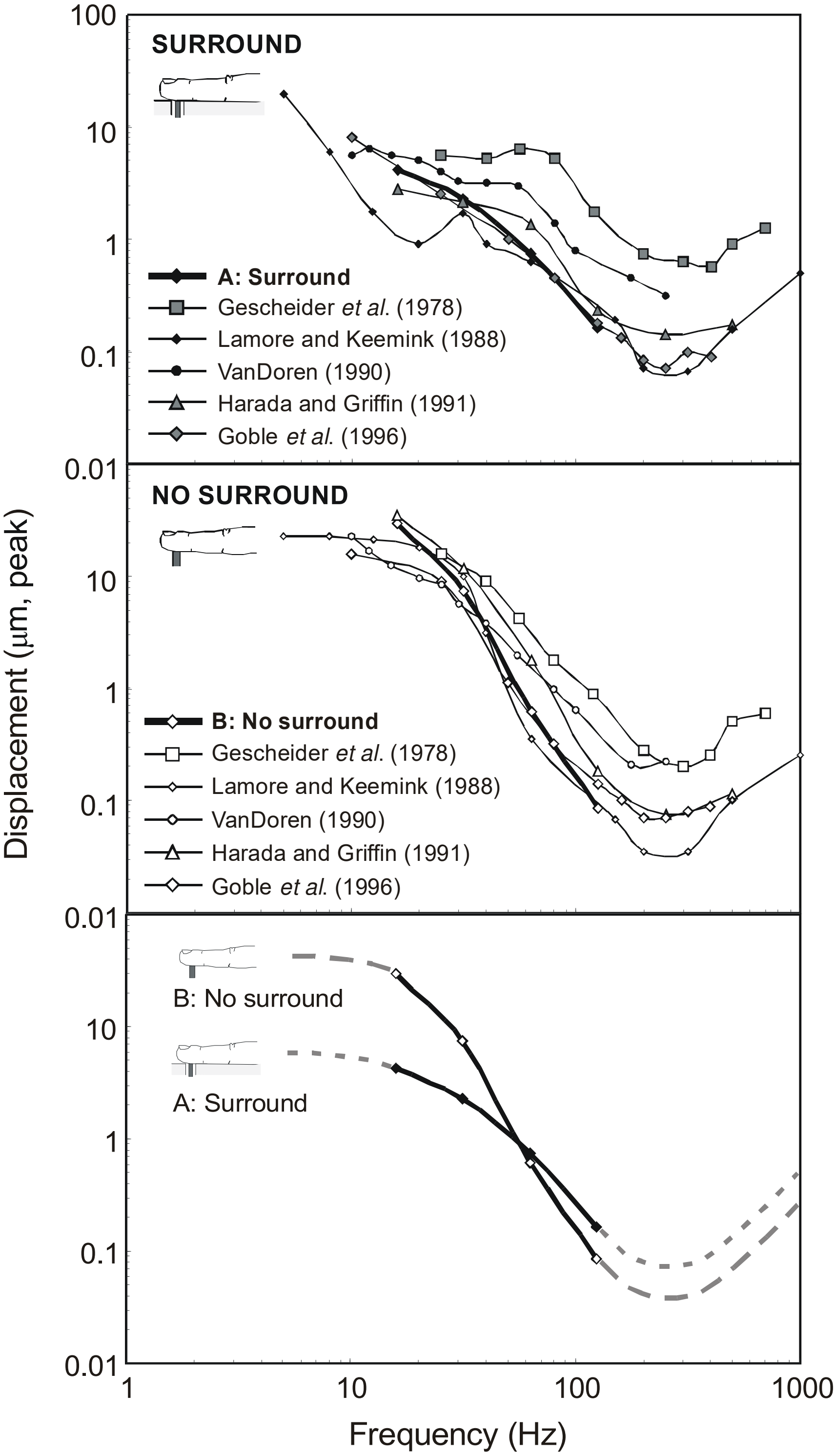
SURROUND
A: Surround
Gescheider et al. (1978)
Lamore and Keemink (1988)
VanDoren (1990)
Harada and Griffin (1991)
Goble et al. (1996)
NO SURROUND
B: No surround
Gescheider et al. (1978)
Lamore and Keemink (1988)
VanDoren (1990)
Harada and Griffin (1991)
Goble et al. (1996)
B: No surround
A: Surround
Displacement (μm, peak)
100
10
1
0.1
0.01
Frequency (Hz)
1
10
100
1000

FIG. 6

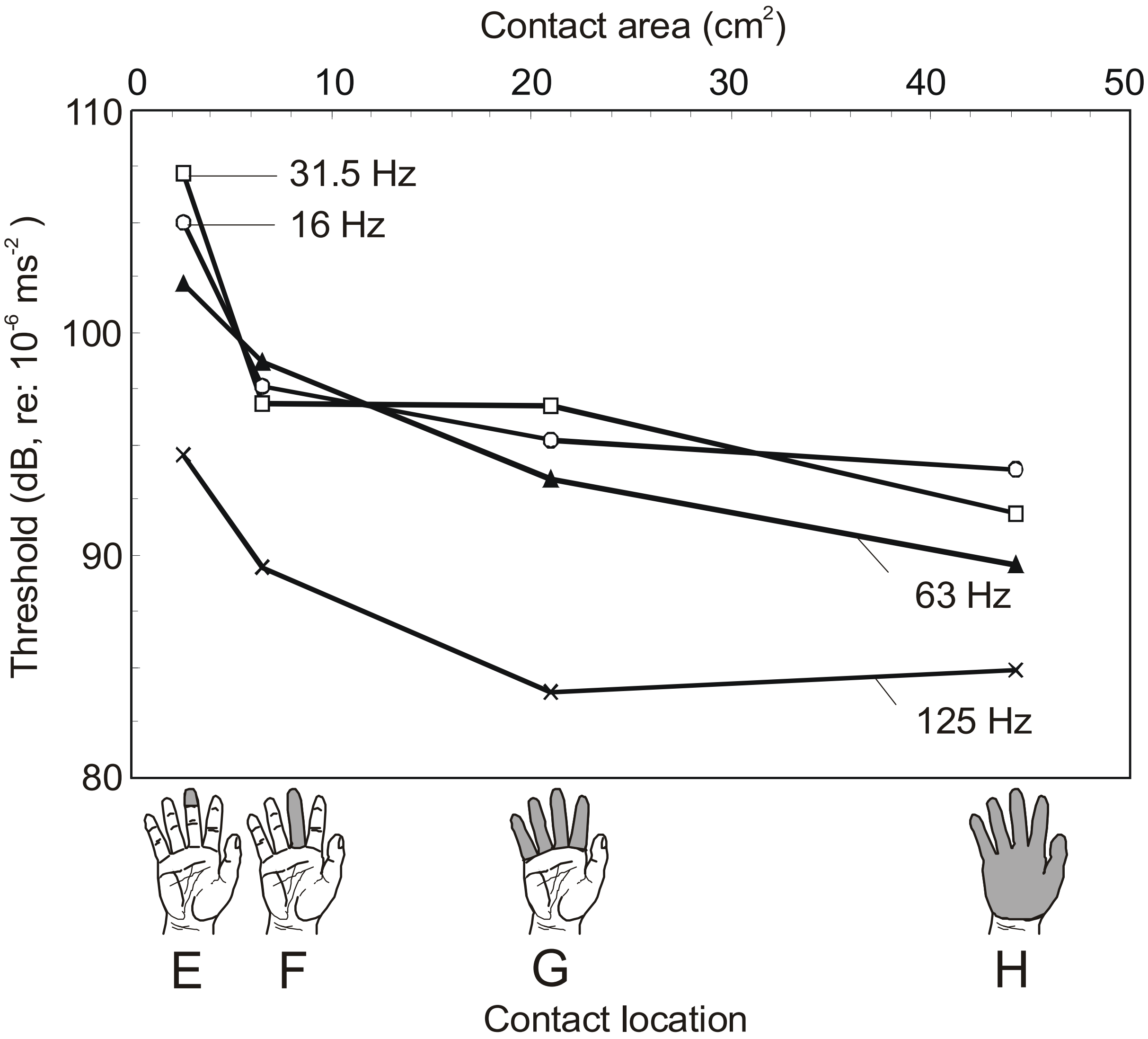
Contact area (cm2)
0
10
20
30
40
50
110
100
90
80
Threshold (dB, re: 10-6 ms-2)
31.5 Hz
16 Hz
63 Hz
125 Hz
E
F
G
H
Contact location

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FIG. 7

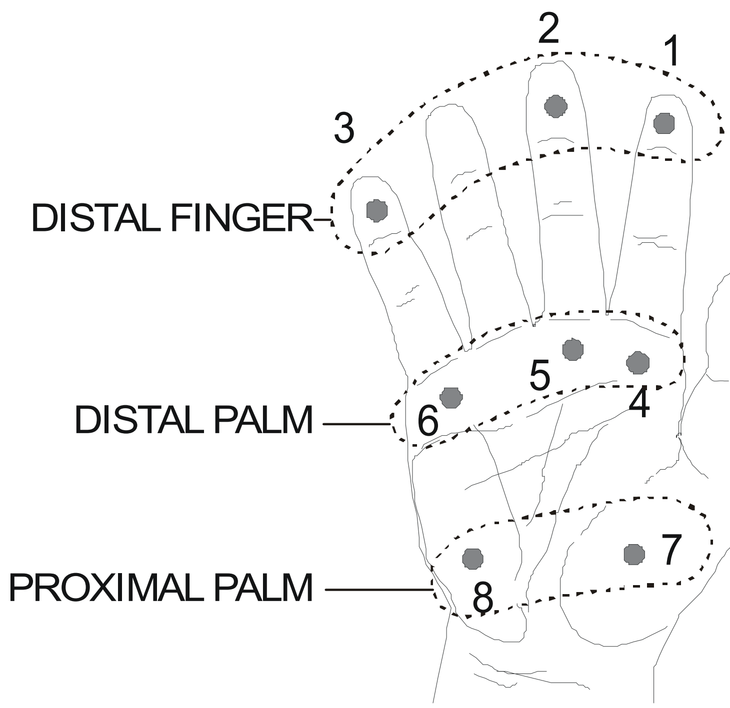

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FIG. 8

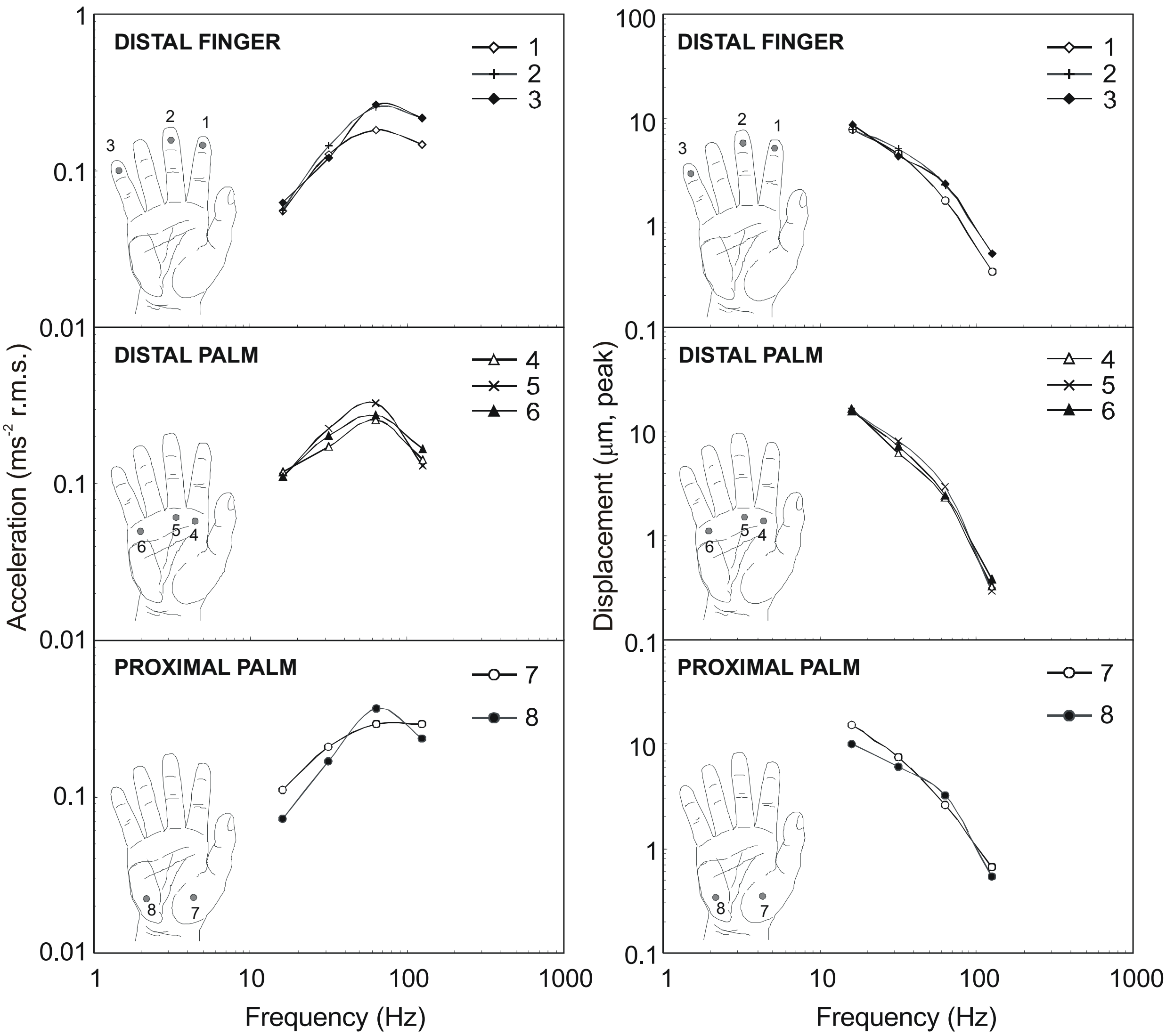
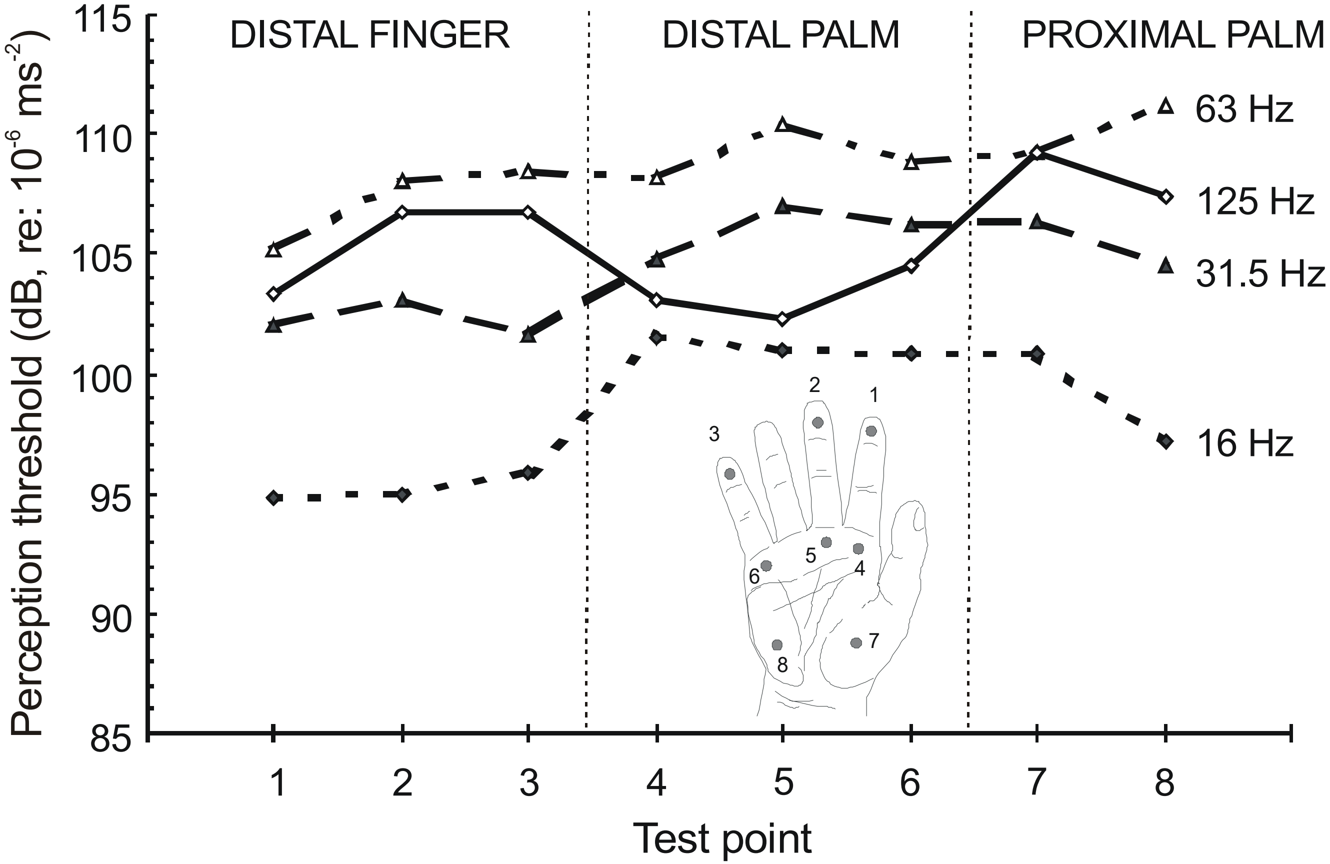


FIG. 9


DISTAL FINGER
DISTAL PALM
PROXIMAL PALM
63 Hz
125 Hz
31.5 Hz
16 Hz
Perception threshold (dB, re: 10^{-6} ms^{-2})
115
110
105
100
95
90
85
1
2
3
4
5
6
7
8
Test point