UNIVERSITY OF SOUTHAMPTON

PSYCHOPHYSICAL INVESTIGATION OF THE PERCEPTION OF HAND-TRANSMITTED VIBRATION

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ABSTRACT

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by Miyuki Morioka

It is desirable to reduce the unwanted vibration from some machinery but retain the wanted (i.e. useful) vibration for the vibrotactile perception of some stimuli. This thesis seeks to understand the sensations produced by hand-transmitted vibration.

Four types of receptor that innervate the glabrous skin of the hand are thought to be responsible for mediating tactile stimuli; they are referred to as either Pacinian or non-Pacinian receptors. A literature review revealed the known characteristics of the Pacinian and non-Pacinian receptor systems. The sensitivity of the Pacinian system changes systematically with changes of contact area, stimulus duration, skin temperature and age, whereas the non-Pacinian systems are less dependent on contact area and stimulus duration, but dependent on stimulus gradients delivered to the skin.

A series of eight psychophysical experiments has been conducted in the laboratory to investigate the perception of hand-transmitted vibration at both threshold and supra-threshold levels so as to investigate factors influencing perception.

Four studies determined absolute perception thresholds (minimum magnitude of stimuli that could be perceived by subjects), examining variables influencing absolute thresholds (i.e. the psychophysical method, the contact position and posture, contact area, contact force, contact location). Significant decreases in thresholds due to increasing contact area (extending from the fingertip to the whole hand) were found. Absolute thresholds were also influenced by stimulus frequency, the psychophysical method and contact conditions, but were similar for two different hand postures (grasping a handle and pressing a plate). The results were partially explained by the reported response characteristics of the Pacinian and the non-Pacinian systems.

Three further studies investigated sensations at supra-threshold levels. A study investigated the variation in the localisation of sensations with varying contact areas; this study investigated whether the dynamic responses of the hand influenced psychophysical ratings of tactile sensitivity. Sensation magnitudes were also determined using the method of magnitude estimation. The results indicated that the frequency dependence of the sensation magnitude was affected by contact area, showing a spatial summation effect. Nevertheless, a study of difference thresholds (minimal change of stimulus magnitude required for subjects to notice a change) showed no frequency dependence between 8 and 500 Hz at either of two reference magnitudes (2 and 5 ms^{-2} r.m.s.).

Identification of independent responses via Pacinian and non-Pacinian was undertaken in the final study so as to provide further understanding of the experimental results. The experiment involved the determination of masked thresholds (a threshold shift caused by another vibration stimulus) at the fingertip and at the whole hand. Thresholds for four pure tone test frequencies (16, 31.5, 63 and 125 Hz) in the presence of each of two $^1/_3$-octave bandwidth maskers (at 16 or 125 Hz) were determined at magnitudes from 0 to 30 dB above the absolute threshold of each masker. Independent responses from the Pacinian receptors and the non-Pacinian receptors were obtained from the masking functions.

It was concluded that contact area is the most important factor modifying sensitivity of the Pacinian system and that this is responsible for the whole hand having lower vibrotactile thresholds than the finger. Moreover, there seem to be three independent receptors within the Pacinian and the non-Pacinian systems (i.e. FA II, FA I and possibly SA II receptors) combining to detect hand-transmitted vibration, with differing sensitivities over the frequency range of interest. The findings from the series of studies extend understanding of the perceptual characteristics of the Pacinian and non-Pacinian systems that are excited by hand-transmitted vibration.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

Technological ingenuity in recent times has made our life extremely easy, replacing primitive manual work with powered tools or machines, but this has resulted in much exposure to hand-transmitted vibration.

Vibration exposure of the hand is produced from vibrating surfaces through contact with the skin of the glabrous area of the hand. Some occupational exposures to hand-transmitted vibration present a risk of injuries at the hand and arms with neurological, vascular and musculoskeletal disorders (Bovenzi, 1990; Griffin, 1990), which are often referred as the hand-arm vibration syndrome (HAVS). Other situations produce hand-transmitted vibration of low magnitude or for short durations (e.g. car steeling-wheels, electric-razors) in everyday life. Although these may not present a significant hazard, the hand-transmitted vibration can cause discomfort, annoyance or fatigue. Reductions of severe exposures to hand-transmitted vibration are usually required, but how should the vibration be reduced? The characteristics of vibration transmitted to the hand from tools are often complex, giving rise to a complex pattern of sensations and various human responses.

Hand-transmitted vibration does not always create such 'unwanted' motions: it can provide 'wanted' stimulation. Operators may require hand-transmitted vibration as feedback from processing tools or the environment. Artificial vibration could also be supplied to the hand as a substitution for other senses (e.g., hearing, vision, speech). The required motion should be perceptible, but not cause adverse effects. It is desirable to optimise the characteristics of hand-transmitted vibration according to the sensations produced by the vibration.

The questions to be asked here are: (i) how well can we perceive vibration via the hands? (ii) how does sensitivity change as a function of the stimulus characteristics and other variables? (iii) what mechanisms are involved in vibration perception? More fundamentally, how is vibration perception produced and how can it be quantified.

Psychophysics is concerned with the relationships between quantities of physical stimuli and the sensory capacity of human observers. Using various psychophysical measurement techniques, it is possible to quantify psychological responses to hand-transmitted vibration. There are other ways to investigate vibrotactile sensitivity. Neurophysiological studies have identified four types of mechanoreceptors innervating the glabrous skin of the hand that are responsible for tactile sensibility. Each receptor has an independent structure and has distinctive characteristics in responding to tactile stimuli. A combination of these two approaches, neurophysiological and psychophysical studies, have identified functions of the mechanoreceptors in the skin. A majority of these studies have been concerned with the glabrous skin in the hand (i.e. hairless skin of the palm and the palmer aspect of the fingers), with little attention to tactile sensation raised by touching a vibrating surface with the whole area of the hand.

This present research has involved the investigation of sensations produced by hand-transmitted vibration using various psychophysical measurement techniques and considering factors affecting perception in order to identify the relevant sensory mechanisms. Three stages have been involved in the research: (i) assessing results and theories from past studies; (ii) obtaining new knowledge from experimental studies of the perception of vibration in the whole hand; (iii) producing theories for the perception of hand-transmitted vibration. In the second stage, comparisons of between perception via the whole hand and perception via the finger allowed the exploration of differences in sensitivity between the fingers and the hand.

1.2 OBJECTIVES OF RESEARCH

The overall objective of the research was to explore how the perception of hand-transmitted vibration depends on characteristics of the vibration and other variables so as to predict ability of human observers to detect hand-transmitted vibration at the hand.

It was expected that sensations produced by vibration of the whole hand would differ from those produced by vibration of the fingertip, due to different mediation via the receptors of the hand. The different form of the stimulus and the different conditions of exposure were expected to result in a different complex pattern of sensations.

The research also seeks to identify the mechanisms responsible for vibration perception at the hand.

1.2.1 Scope of the research

In order to fulfil the main objective, the scope of the research was as follows:

i) Exploration of how perception thresholds change as a function of the stimulus and other variables;

ii) Comparison of vibrotactile sensitivity on the whole hand and the fingertip;

iii) Identification of mediation characteristics via receptors and how they interact to produce perception at the hand.

1.3 POSSIBLE APPLICATIONS OF THE RESEARCH

Although this research was aimed to provide fundamental knowledge, it may assist:

i) understanding of sensory mechanisms involved in hand-transmitted vibration,

ii) the assessment of hazards arising from the use of vibrating tools,

iii) the reduction of vibration on machinery, and

iv) the improvement of tactile communication for the disabled.

The possibilities of these applications are recollected in conclusions (Chapter 13).

1.4 ORGANISATION OF THESIS

The structure of the thesis, with a brief description of each chapter, is displayed in Figure 1-1.

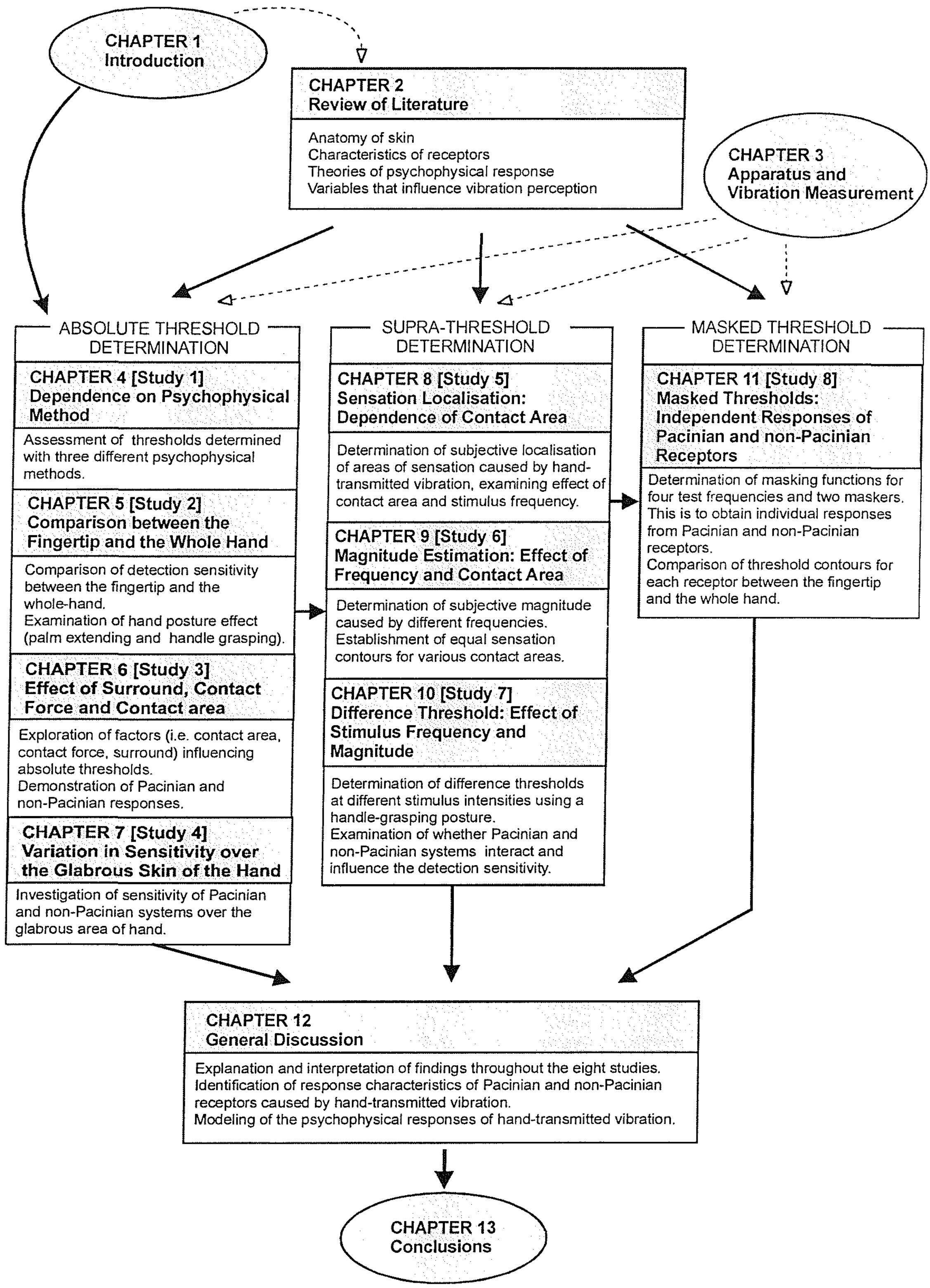


Figure 1-1 Structure and overview of the thesis.

The first chapter provides a general background of the research, defining the objectives and the scope of the research. This chapter also introduces the laboratory studies conducted in the research.

Chapter 2 presents a literature review: it summarises the state of knowledge for mechanisms involved in producing vibration perception at the hand, introduces available psychophysical measurement methods, and identifies factors influencing vibration perception.

Chapter 3 describes the apparatus used in the laboratory studies, which are described in Chapters 4 to 11.

Chapter 12 presents a general discussion and is followed by the conclusions in Chapter 13.

The laboratory studies presented in Chapters 4 to 11 are summarised below (Section 1.4.1).

1.4.1 Laboratory studies

Eight laboratory experiments were conducted so as to determine the following psychophysical quantities:

Absolute thresholds	Minimum magnitude of stimuli perceived by subjects
Difference thresholds	Change of stimulus magnitude needed for subjects to notice that the magnitude has changed
Sensation magnitude	Impression of stimulus 'size' as experienced by a subject
Localisation of sensation	Location of sensation as judged by a subject
Masked thresholds	Threshold shifts caused by other vibration stimuli

Each of the eight experiments was designed to examine several independent variables in order to test specific hypotheses. A frequency dependence of psychophysical quantities was tested in all experiments, because it is well known that effects of vibration depend on stimulus frequency. The experimental methods employed in each study are summarised in Table 1-1.

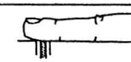
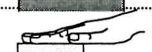
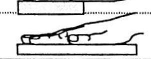
For Studies 5 and 6, the experiments have been assisted by Mr. Ashley Punter with his B.Sc. project (Punter, 2000).

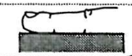
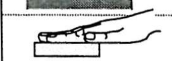
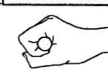
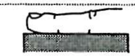
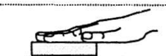
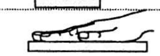
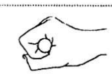
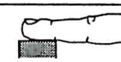
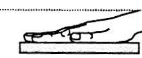
All experiments were approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton (ISVR Technical Memorandum No. 808, 1996).

Table 1-1 Study titles and the independent variables

Psychophysical quantity	Study title	Independent variables
Absolute threshold	Study 1 Dependence on psychophysical method	• Psychophysical method • Stimulus frequency (16-125 Hz)
	Study 2 Comparison between the fingertip and whole hand	• Contact position (fingertip and whole hand) and hand posture • Stimulus frequency (8-500 Hz)
	Study 3 Effect of surround, contact force, and contact area	• Contact condition (surround, contact force and contact area) • Stimulus frequency (16-125 Hz)
	Study 4 Variation in sensitivity over the glabrous skin of the hand	• Contact location within glabrous area of the hand • Stimulus frequency (16-125 Hz)
Localisation of sensation	Study 5 Dependence of contact area	• Contact condition • Stimulus frequency (8-125 Hz) • Stimulus magnitude (2 and 4 ms^{-2} r.m.s.)
Sensation magnitude	Study 6 Effect of stimulus frequency and contact area	• Contact condition • Stimulus frequency (8-125 Hz) • Stimulus magnitude (2 and 4 ms^{-2} r.m.s.)
Difference threshold	Study 7 Effect of stimulus frequency for two stimulus magnitudes	• Stimulus frequency (8-125 Hz) • Reference magnitude (2 and 5 ms^{-2} r.m.s.)
Masked threshold	Study 8 Independent responses of Pacinian and non-Pacinian receptors	• Contact condition (fingertip and whole hand) • Stimulus frequency (16-125 Hz) • Masker frequency (1/3 octave-band vibration centred at 16 or 125 Hz) • Masker intensity (0-30 dBSL)

Table 1-2 Summary of experimental design for eight studies conducted in the research

Study number	Psychophysical quantity	Principal independent variables	Vibration stimuli	Procedure			Contact conditions			Subjects	
			Frequency/Magnitude	Method	Duration	Step rate	Position and Location	Contactor size	Force (N)	Number (M/F)	Age (mean years)
Study 1	Absolute threshold	Psychophysical method	16, 31.5, 63, and 125 Hz	Up-down 2IFC	1.0 sec.	2.0 dB		6mm ∅ contactor 2mm gap	1N	12 (M)	22-27 (24.4)
				Up-down yes-no							
				Békésy yes-no	30 sec/test	3.0 dB/sec					
Study 2	Absolute threshold	Contact position	8, 16, 31.5, 63, 125, 250 and 500 Hz	Up-down 2IFC	3 sec.	2.0 dB		200 x 150mm plate	10N	12 (M)	22-33 (24.6)
		Hand posture						30mm ∅ handle	10N		
								6mm ∅ contactor 2mm gap	1N		
Study 3	Absolute threshold	Contact conditions	16, 31.5, 63, and 125 Hz	Up-down 2IFC	1.0 sec.	2.0 dB		6mm ∅ contactor 2mm gap	1N	12 (M)	22-32 (24.3)
								6mm ∅ contactor without surround	1N		
								35mm ∅ contactor	1N/ 5N		
								120 x 22 mm plate	5N		
								120 x 120mm plate	5N		
								220 x 150 mm plate	5N		
Study 4	Absolute threshold	Contact location	16, 31.5, 63, and 125 Hz	Békésy yes-no	30 sec/test	3.0 dB/sec		6mm ∅ contactor 2mm gap	1N	12 (M)	22-32 (25.9)

Study number	Psychophysical quantity	Principal independent variables	Vibration stimuli Frequency/Magnitude	Procedure			Contact conditions			Subjects	
				Method	Duration	Step size	Position and Location	Contactor size	Force (N)	Number (M/F)	Age (mean, years)
Study 5	Localisation of sensation	Contact condition	8, 16, 31.5, 63 and 125 Hz	-	5.0 sec	-		35mm ∅ contactor	1 N	20 (M)	18-25 (20.4)
			Intensities = 2.0 and 4.0 ms^{-2}					120 x 22 mm plate	1 N		
								120 x 120mm plate	5 N		
								220 x 150 mm plate	5 N		
								30mm ∅ handle	5 N		
Study 6	Sensation magnitude	Contact condition	8, 16, 31.5, 63 and 125 Hz	ME	2.0 sec	-		35mm ∅ contactor	1 N	20 (M)	18-25 (20.4)
		/stimulus frequency	Intensities = 2.0 and 4.0 ms^{-2}					120 x 22 mm plate	1 N		
			Reference = 31.5 Hz					120 x 120mm plate	5 N		
								220 x 150 mm plate	5 N		
								30mm ∅ handle	5 N		
Study 7	Difference threshold	Vibration frequency /magnitude	8, 16, 31.5, 63, 125, 250, and 500 Hz ref. = 2 and 5 ms^{-2} r.m.s.	Up-down 2IFC	2.0 sec	0.2 dB		30mm ∅ handle	10N	8 (M)	23-28
Study 8	Masked threshold	Masker intensity	16, 31.5, 63, and 125 Hz = test stimuli	Up-down 2IFC	0.6 sec.	2.0 dB		35mm ∅ contactor	1N	6 (5M/1F)	18-27 (23.2)
			16 or 125 Hz centred 1/3octave noise = masker					220 x 150 mm plate	5N		

2IFC = Two-interval forced-choice procedure   ME = Magnitude Estimation method   M/F = Male / Female

CHAPTER 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

Feeling by touch is an 'exploration of the world': it is one of the ways we have of receiving from, and responding to the outside world. Touch is a general term, including passive (tactile) and active (haptic) sensation of the skin (Schiff and Foulke, 1982). Many scientists have investigated sensory events, and some have formulated laws relating sensations to the physical events that cause them. This required the development of methods of measuring sensations.

The interaction between physiological and psychological approaches to the tactile sensory processes has been fruitful. A full of appreciation of the discoveries is of importance to the present studies. This chapter assembles current knowledge of the physiological and psychophysical responses to hand-transmitted vibration, introducing anatomical and physiological information on skin senses, relevant psychophysical measurement methods and factors influencing the perception of hand-transmitted vibration.

2.2 SKIN SENSE

2.2.1 Anatomy of the skin

When we come to consider the sensation aroused in the skin, one would ask how many skin senses are there. The classification of skin senses has been logically separated into three kinds of cutaneous receptors: (i) mechanoreceptors, (ii) thermoreceptors and (iii) nociceptors (Carpenter, 1995) [see Table 2-1].

Table 2-1 Three kinds of cutaneous receptors corresponding to three sensory modalities.

Cutaneous receptors	Sensory modalities
Mechanoreceptors	pressure, vibration and stretching (rapid or sustained touch)
Thermoreceptors	cold, warmth (changes in temperature)
Nociceptors	pain (physical damage of tissues)

It may be possible that more than one cutaneous end organ are involved for producing the complex pattern of sensations - for example, mechanical pressure and thermal change - which a particular receptor may be selected causing onset or offset of response.

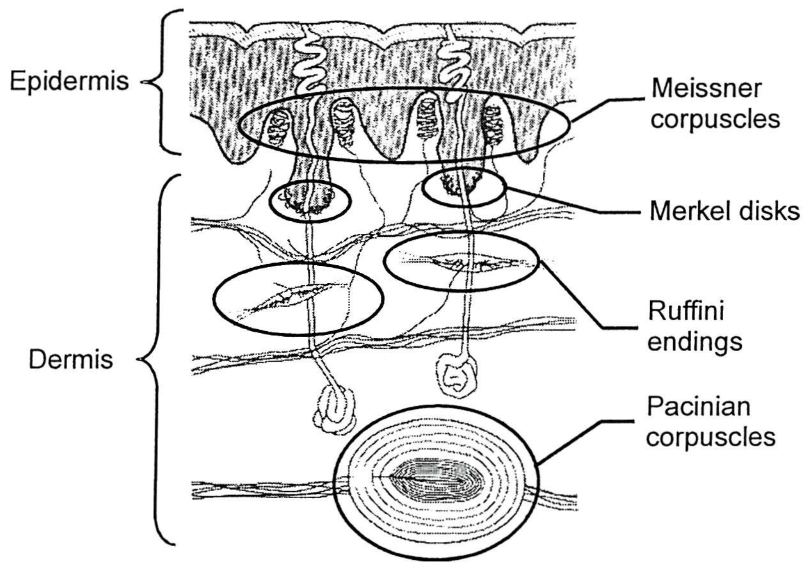


Figure 2-1 Schematic representation of cross-section of skin. (Figure from Geldard, 1953).

For vibration sensation, there are four types of receptors innervating the skin and mediating the vibration stimuli (see the corresponding location in Figure 2-1):

Meissner's corpuscles

Pacinian corpuscles

Merkel's discs

Ruffini endings

According to a comprehensive morphological study undertaken in the hairless skin of the human fingers, Cauna (1958) reported that these sensory endings (receptors) are dynamic structures which undergo a continuous transformation throughout the lifetime of an individual, apparently in response to changing functional requirements. The descriptions of each receptor reported by Cauna (1958) (except Ruffini endings) and also by Johansson and Vallbo (1983) are briefly summarised in Table 2-2:

2.2.2 Neurophysiological investigation

Most neurophysiological studies have been made since the 1920s when Adrian and Zotterman (1926) first demonstrated the basic nature of the message originating from cutaneous mechanoreceptors of the frog. The related research mostly involved microneurographic techniques of recording impulse activity from single nerve fibres and revealed four types of mechanoreceptive units innervating the human glabrous skin. The units were distinguished on the basis of their adaptation to sustained skin deformation and structure of the cutaneous receptive field: FA I, FA II, SA I and SA II (e.g. Johansson, 1976, 1978; Johansson and Vallbo, 1979a, 1980; Knibestöl and Vallbo, 1970; Mountcastle *et al.*, 1969; Talbot *et al.*, 1968; Vallbo and Johansson, 1984).

2.2.2.1 Receptor sensory properties

The receptors have distinctive properties and are usually classified as having fast or slow adaptation (FA or SA), and small or large receptive field (type I or type II). The centre boxes of Figure2-2 show the nerve impulse discharge (lower trace) in response to a perpendicular ramp indentation of the skin (upper trace) for each unit type. The fast-

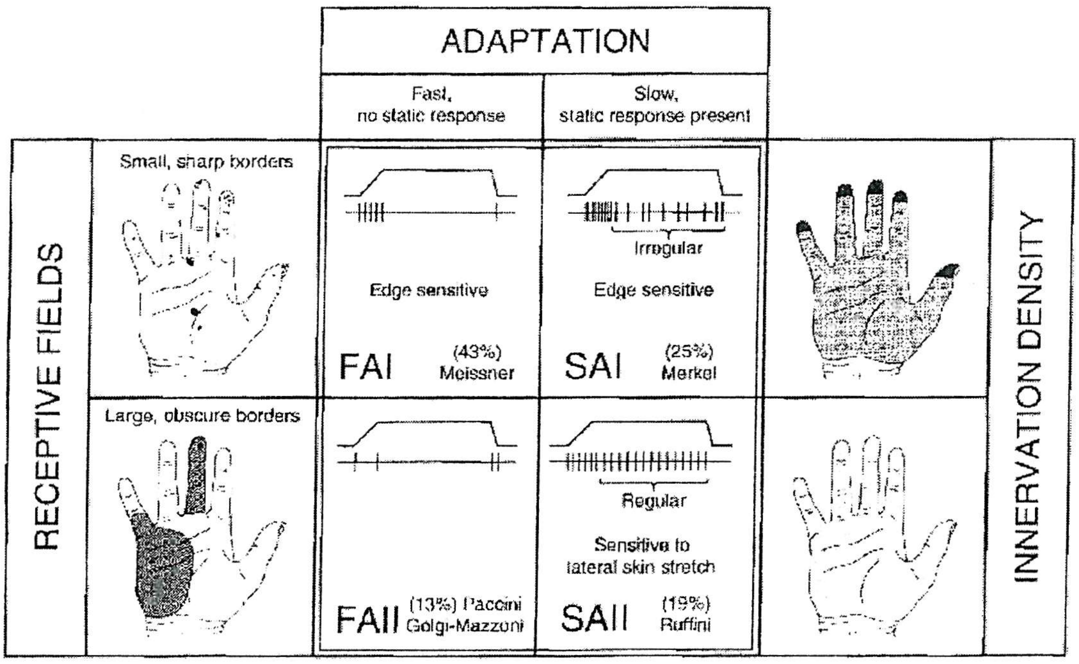


Figure 2-2 Characteristics of the four types of mechanoreceptive afferent units innervating the glabrous skin of the human hand. (Figure from Greenspan and Bolanowski,1996, reproduced from Westling, 1986).

adapting units, particularly the FA II receptors, respond not only when the indentation is increasing, but also when the stimulus is withdrawn. The fast adapting mechanoreceptors (FA I and FA II) exhibit higher sensitivity to stimulus velocity than slowly adaptive receptors, whereas the slow-adapting receptors exhibit a sustained discharge during constant skin indentation in addition to their discharge during initial skin indentation (see upper boxes of Figure 2-2) (Johansson and Vallbo, 1983).

It has been reported by Johansson and Vallbo (1979a) that there are about 17,000 tactile units supplying the glabrous skin areas of the hand. Different populations of receptors exist in the glabrous skin of the human hand. As seen in Figure 2-2 (right boxes), the FA I and the SA I receptors are highly distributed at the distal part of the digits, whereas the FA II and the SA II receptors are almost evenly distributed over the glabrous area of the skin. Each of these four receptors has been identified with a specialized structure within the skin: the FA I with the Meissner corpuscles, the FA II with the Pacinian corpusles, the SA I with the Merkel discs, and the SA II with the Ruffini endings (see review by Vallbo and Johansson, 1984). The functions of each mechanoreceptor representing tactile performance is summarised in Table 2-2.

Table 2-2 Summary of characteristics of four mechanoreceptors (location, structure, aging and function).

Meissner's corpuscles (FA I)	
Location	In the papillae of the papillary ridges of the dermis.
Structure	Surrounded by an elastic capsule, which is attached to the epidermis above, and to the general elastic framework of the corium below.
Aging	Two gradual changes: first, the epidermal attachment becomes less intimate; second, due to a continuous longitudinal growth, the corpuscles become coiled, their upper extremity becomes separated from the epidermis, some of them undergo atrophy and are subsequently lost.
Function	Small well-defined receptive fields adapting rapidly to a sustained stimulus Approximately 40 percent of all the tactile receptors in the glabrous skin. Sensitive to edge contours of objects indenting the skin: capable of localisation of objects in contact with the skin. FA I also displays the highest activity with a increase and a release of grip force. Some FA I units also discharge during periods of physiological muscle tremor.

Pacinian corpuscles (FA II)	
Location	In the deeper layers of the skin as well as in the subcutaneous tissues of the dermis. They have a wide distribution in the human body, (e.g. in the viscera, around joints and muscle tendons) in the skin, they are only found in the deeper layers of hairless skin.
Structure	A thick myelinated axon which enters the central core or the 'inner bulb' of the corpuscle and ends in terminal enlargements. The bulk of the corpuscle or the 'outer bulb' consists of cellular lamellae, which are arranged in a concentric manner around the central core.
Aging	The shape of the Pacinian corpuscle in the adult becomes no longer oval, but irregular to a varying degree. They are remodelled, new corpuscles are being formed on the axons of older ones, and then many original corpuscles are lost. As a result, up to 90 percent of these corpuscles may be lost in old age; the loss is more rapid and extensive in the male.
Function	Wider fields with indefinite borders. About 13 percent of all mechanoreceptors in the glabrous skin of the hand. Most sensitive to high frequency of stimuli ranging between 100 and 300 Hz. Not being capable in detection of stimulus location, but the sensitivity is broadly distributed.
Merkel's disks (SA I)	
Location	At the deep surface of the intermediate or sweat ridge.
Structure	Thick myelinated nerve fibres with the associated cells constitute Merkel's corpuscles.
Aging	The receptor organs seem to undergo relatively little change with age. Some terminal nerve fibres become enlarged, especially in males. Such enlarged endings may cover more than single epidermal cells.
Function	Small and well defined receptive field. Sensitive to gradient stimuli indenting the skin, being capable of discrimination, such as two point and gap detections.
Ruffini endings (SA II)	
Location	In the dermis layers.
Structure	The nerve terminals are intermingled with collagen fibrils longitudinally passing through the corpuscle and anchoring the corpuscle in the dermal collagen at its poles. Having a thin spindle-shaped capsule.
Aging	Not studied.
Function	Large receptive fields with indefinite boundaries. Sensitive to lateral skin stretching (may sensitive to stimulus direction). Also capable of responding to static stimuli and joint movements of the hand and finger.

2.2.2.2 Detection sensitivity to vibration stimuli

Attempts have been made to measure neural responses from single nerve cells in human subjects and subhuman species using vibrotactile stimuli. Sato (1961) initially determined physiological thresholds of isolated Pacinian corpuscles using two types of vibration stimuli (i.e. sudden increases of vibration and slow increases of vibration) at frequencies from 20 to 100 Hz, by recording impulses from the axon of cat. It was found that the optimal frequency for stimulation of the Pacinian corpuscle was around 150-200 Hz. The threshold increased as the frequency decreased below 150 Hz. Subsequently, investigations have been expanded to the sensitivity of other receptors. Iggo and Ogawa (1977) presented separate physiological thresholds from three afferent units, as shown in Figure 2-3. It is seen that FA II and SA receptors were clearly differentiated with characteristics patterns of discharge to ramp stimulation. The SA units are sensitive at frequencies of 5 Hz, or less, FA II units are most sensitive in the range 100 to 300 Hz, while the 'tuning curve' of the FA I units (often referred to as RA, rapidly adapting, for subhuman receptor) are relatively flat, with the lowest frequencies at 10-20 Hz.

Mountcastle and co-workers provided further understanding of tactile mechanisms by combining neurophysiological and psychophysical methods (LaMotte and Mountcastle, 1975; Mountcastle *et al.*, 1967, 1972).

2.3 MEASUREMENTS OF VIBRATION PERCEPTION IN PSYCHOPHYSICS

In general, sensations increase with increases in the magnitude of the stimulus (or stimulus difference) that gives rise to the sensation. The sensory capacity of humans is abstract, and includes negative and positive reactions.

Psychophysics is the scientific study of the relationship between stimulus and sensation, more specifically, the relationship between sensations, Ψ, in the psychological domain and stimuli, φ, in the physical domain (see Gescheider, 1985). Since reactions to stimuli are variable, the perception must be specified as a statistical value. Psychologists and statisticians have dedicated their careers to the development of psychophysical measurement methods.

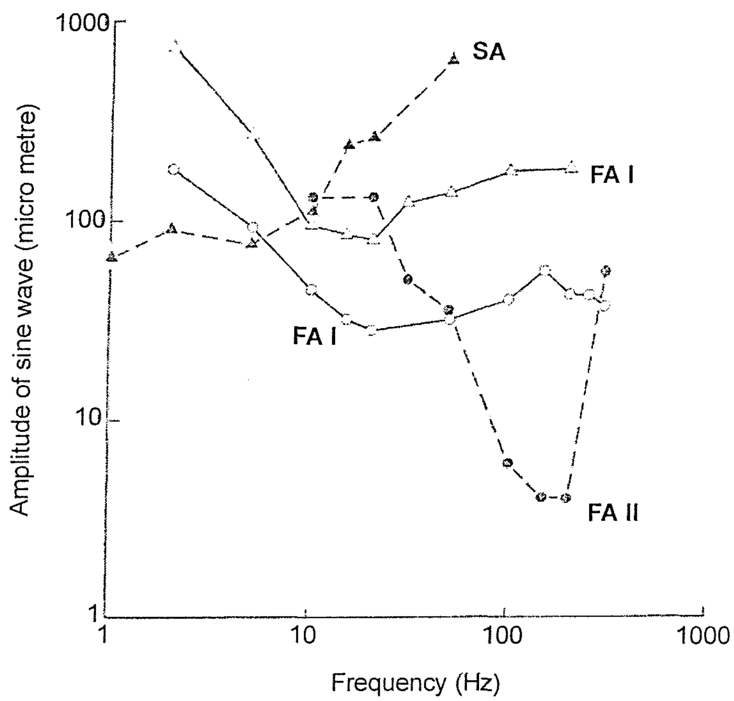


Figure 2-3 Tuning curves of glabrous skin in the cat. (Figure from Iggo and Ogawa, 1977).

This section defines psychophysical quantities, describes the classical methods for quantifying perception and presents the main theories of psychophysics.

2.3.1 Concept of 'threshold'

One could think that the threshold represents a sharp transition point between 'sensation' and 'no sensation'. However, the value of the threshold is assumed to vary over time, according to the condition of the sensory nervous system. An observer may give a positive response ('yes') to a stimulus at a particular intensity, but this 'momentary threshold' fluctuates randomly from moment to moment. Repeated trials with various stimulus intensities are therefore required to obtain a distribution of 'momentary thresholds'. It is assumed that a positive response is expected only when the stimulus intensity is equal to, or greater than, the 'momentary threshold' value. For instance, a weak stimulus makes the decision difficult and results in the exceeding the 'momentary thresholds' in only a small percentage of total trials. In contrast, a strong stimulus exceeds the 'momentary thresholds' in a high percentage of trials. The early psychophysicists typically choose 50% detection as the best estimate of the threshold (Gescheider, 1985).

There are arguments and evidence against this classical concept of the threshold, such as 'response bias': the probability that observer responses may be affected by their expectation of the presence or absence of the stimulus, and also by 'payoff'. It is therefore necessary for the stimuli and other matters to be carefully controlled.

2.3.2 Psychophysical Quantities

2.3.2.1 Absolute thresholds

An absolute threshold is the stimulus amount which is just sufficient for the presence of the stimulus to be detected. Psychophysical thresholds can be defined by statistics indicating the probability of detection for some value of the stimulus. This is also called the 'detection threshold'. Absolute threshold contours for vibration stimuli are often expressed as a function of frequency.

2.3.2.2 Supra-threshold detections

2.3.2.2.1 Difference thresholds

A difference threshold is the difference in value of two stimuli which is just sufficient for the difference between the stimuli to be detected. Also called a differential threshold, a difference limen (= DL), a just noticeable difference (= JND). Difference thresholds for vibration stimuli have been determined for change of stimulus magnitude and for a change of stimulus frequency. Weber's fraction (see Section 2.3.4.1) is often presented.

2.3.2.2.2 Equal sensation levels

In contrast to difference thresholds, equal sensation levels are the magnitudes of stimuli that produce broadly similar degrees of sensation ('just not noticeable difference' = JNND). Equal sensation contours are often expressed as function of frequency.

Figure 2-4 shows equal sensation contours for vibration stimuli with a reference at 250 Hz as determined by Verrillo *et al.* (1969) and Verrillo (1970), they were measured at the thenar eminence employing a 2.9 cm^2 contactor area with 1.0 mm of a surround gap. Figure 2-5 shows equal sensation contours from Maeda and Iwata (1983) obtained with whole hand contact. Although these are expressed in different scales (i.e. displacement, acceleration), it is generally seen that the equal sensation contours are a similar shape to the absolute threshold contours, being gentle curves with increasing stimulus magnitude.

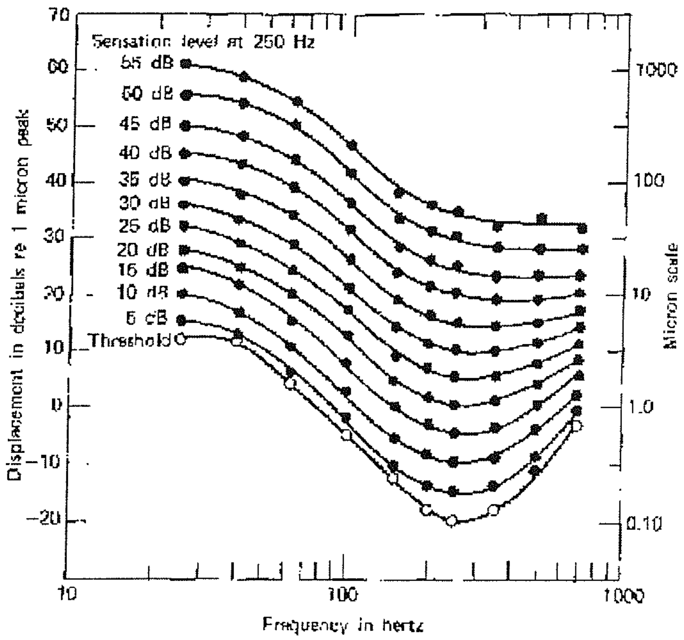


Figure 2-4 Equal-sensation contours at the thenar eminence. 2.9 cm^2 contactor area, 1.0 mm of gap. (Figure from Verrillo, 1970).

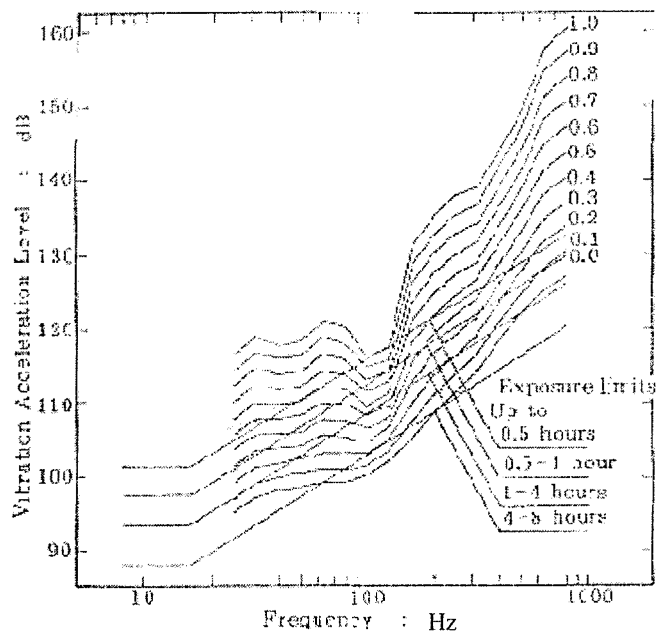


Figure 2-5 Equal-sensation contours for whole hand (handle grasping posture). Reference at 100 Hz. (Figure from Maeda and Iwata, 1983).

2.3.2.2.3 Sensation magnitude

It is often the case that a sensation magnitude does not increase by the same amount (i.e. percentage) as an increase in the stimulus magnitude. The measurement of sensation magnitudes for vibration stimuli are undertaken in order to: (i) determine the growth of sensation (see Section 2.3.4.3: Steven's power law) as a function of magnitude at various frequencies; (ii) establish contours of equal subjective intensity; (iii) compare the psychophysical methods of direct scaling and intensity matching for a wide range of intensities and frequencies. Verrillo (1970) examined sensation magnitudes at eleven magnitudes and ten frequencies between 25 and 700 Hz using two different methods (i.e. direct intensity scaling, inter-frequency intensity matching). Equal sensation contours were determined (for the equal sensation contours obtained by direct intensity scaling, see Figure 2-4), and found to produce similar results with both methods.

2.3.2.3 Masked thresholds

When an auditory signal is immersed in noise, how does the threshold for a pure tone, or for speech, vary with the level of the masking noise and with the stimulus frequency? Hawkins and Stevens (1950) raised the question and developed an approach to the problem.

Vibrotactile masking has been studied with two major objectives: (i) to determine how various parameters of the masking conditions influence stimulus detection, for example, the effect of masker locus (Gilson, 1969a; Sherrick, 1964), the number of masking stimuli (Gilson, 1969b; Verrillo and Gescheider, 1983), the psychophysical method (Alluisi *et al.*, 1965; Gescheider *et al.*, 1989; Gilson, 1974; Snyder, 1977); (ii) to identify separate vibrotactile information processing receptors (e.g. Bolanowski *et al.*, 1988; Craig, 1976; Ferrington *et al.*, 1977; Gescheider *et al.*, 1982, 1983, 1985; Hamer *et al.*, 1983; Labs *et al.*, 1978; Makous *et al.*, 1996a) (see masking theory in Section 2.4.4).

Masking is a phenomenon in which the perception of a normally detectable stimulus is impeded (has an elevated threshold) as a consequence of the presence of a second stimulus. The second stimulus may be presented at a different point in the same sensory system to cause 'lateral masking'. Alternatively, it may be presented at a different time, either before (for 'forward masking'), or after (for 'backward masking') of the test stimulus. It seems the amount of threshold shift depends on the timing of the masker as well as the type of masker. Gescheider *et al.* (1989) examined the form of masking functions for forward, backward, and simultaneous masking in three different stimulus conditions. The 50 ms test stimulus was presented in phase with the 700 ms masker. More simultaneous masking was observed when the sinusoidal test stimuli were detected in the presence of noise than when they were detected in the presence of sinusoidal maskers of the same frequency. The greatest amounts of masking tended to occur near the onset and just after the termination of the *masking stimulus*. This difference in amount of masking disappeared when the test stimulus was expressed in terms of the increment in energy, as shown in Figure 2-6. The rates of decay were similar between backward and forward masking with both high (250 Hz) and low (25 Hz) frequencies. This suggests similarities in stimulus processing between Pacinian and non-Pacinian systems (see Section 2.4.1 re: duplex theory).

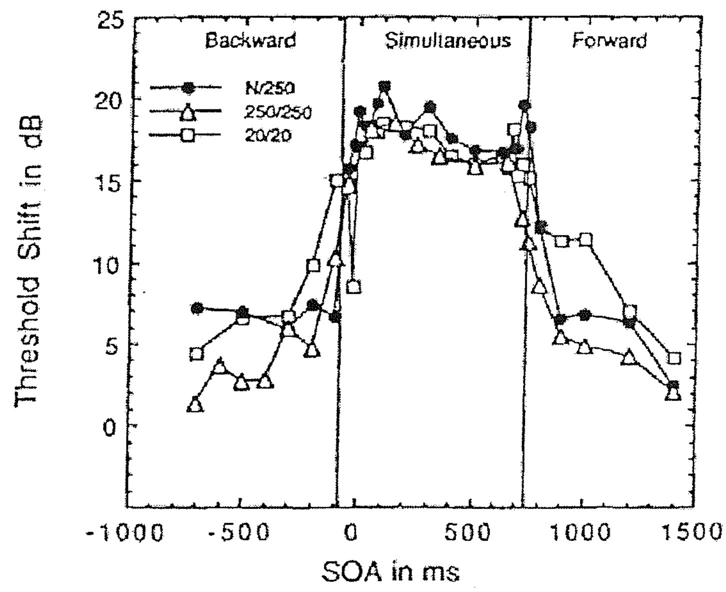


Figure 2-6 Threshold shifts in dB as a function of SOA (= stimulus onset asynchrony). Average masking functions with test stimulus expressed as an increment in energy. (Figure from Gescheider *et al.*, 1989).

A follow-up study by Makous *et al.* (1996) determined vibrotactile thresholds with varying delays between the masking and the test stimuli, from 5 to 995 ms. It was found the decay in the effect of the masking stimulus was different for the two receptor systems: the Pacinian system decayed at more than twice the rate of the non-Pacinian system when the masking stimulus levels were well above threshold (i.e. 10 dB or greater).

2.3.3 Psychophysical Measurement Methods

Fechner recognised the statistical nature of thresholds and the methodological consequences. Since then, psychologists have been indebted to him for developing three methods for measuring thresholds: 1) the method of constant stimuli; 2) the method of limits; 3) the method of adjustment. Each of these methods involves an experimental procedure and a mathematical treatment of data.

Having chosen a psychophysical method, it is necessary to decide how to obtain responses from subjects. There are three basic procedures: (i) yes-no procedures; (ii) forced-choice procedures; (iii) scaling procedures.

Some of methods have been developed for sensory threshold measurements. Three popular techniques are introduced in this section: (a) up-down (staircase) method; (b) von Békésy method; and (c) magnitude estimation method (see Gescheider, 1985, Guilford, 1954; Savage, 1970; Stevens, 1975 for more details of measurement methods).

2.3.3.1 Classical methods

2.3.3.1.1 Method of constant stimuli

The method of constant stimuli is the procedure of repeatedly using the same stimulus, (usually between five and nine different values) throughout the experiment. The stimuli are presented at random so that the subject cannot anticipate the stimulus sequence. This method allows the determination of the percentage of detections as a function of stimulus intensity, φ. The disadvantage of this procedure is that it is time consuming during measurement, and preliminary experiment is necessary to obtain some idea of the required range of stimuli.

2.3.3.1.2 Method of limits

The method consists of presenting several of ascending and descending series. The starting point is set below or above the threshold level and then the stimulus is increased or decreased by small steps. The series is stopped when a subject responds. The disadvantage of the method is the possibility of learning and fatigue effects, because the procedure may be predicted by a subject and the experiment tends to last a long time.

2.3.3.1.3 Method of adjustment

With method of adjustment, observers are to adjust a stimulus to which they are exposed until it is subjectively equal to, or in some desired relation to, a specified criterion. One of the main features of this method is the opportunity afforded to an observer to control the changes in the stimulus, however, this can be a disadvantage and the resulting data may not be as reliable.

2.3.3.2 *Psychophysical procedures*

2.3.3.2.1 Yes-no procedure

With the yes-no procedure, observers are given a series of trials and they are asked to judge the presence or absence of a signal. The receiver-operating characteristic curve (ROC curve) depends on variation of signal probability, or payoff, conditions. It is recommended that some trials containing no signal are randomly presented.

2.3.3.2.2 Forced-choice procedure

The forced-choice procedure is a technique presenting a trial which consists of two or more observation intervals, and observers are asked to report which observation interval contains a signal. The order of presenting observation intervals is usually randomised. Since this procedure allows observer to guess the presence of stimuli, namely, it does not depend on the observer's criterion, it is attractive for determining stimuli that produce a constant percentage of correct responses. For example, a simple two-interval forced-choice procedure (2IFC) may be used to define conditions that result in 75% correct responses.

2.3.3.2.3 Scaling procedures

With scaling procedures, relatively large number of stimuli can be judged with reference to one another. Instead of asking observers positive or negative (yes or no) answers, it forces observes to scale their judgements reflecting some attribute of the signal(s). The scale can have nominal, ordinal, interval or ratio characteristics. For instance, the observers may be instructed to respond 'five' if a signal was presented for sure, 'four' if fairly sure a signal was presented, 'three' if not sure, 'two' if fairly sure a signal was not presented; and 'one' if a signal was not presented for sure. Another example, the observers are presented with a set of two stimuli and are asked to judge which stimulus is greater, 'five' if the first stimuli is far greater than the second, 'four' if the first is fairly greater than the second, 'three' if both are the same, 'two' if the second is fairly greater than the first, and 'one' if the second is far greater than the first.

2.3.3.3 Variation of method

2.3.3.3.1 Up-down (staircase) method

The up-down (staircase) method is a variation of the method of limits, which has been often employed to determine sensory thresholds. Observers are presented with a sequence of stimuli which progressively increase or decrease in some attribute by small steps. When the observer's response alters, the stimulus value is recorded and the direction of the stimulus sequence is reversed from ascending to descending, or vice versa. The procedure continues until a sufficient number of reversal points have been recorded. The threshold is often taken as the average of those reversal points. This method saves a great amount of time because stimuli that are always presented close to threshold levels. This method can be used in conjunction with the yes-no procedure of the forced-choice procedure.

Wetherill and Levitt (1965) introduced particular rules for the ascending and descending up-down method so as to obtain different percentages of correct responses. For example, with a two-down one-up rule (after two consecutive correct responses the intensity of the stimulus is decreased by a certain step, and after each incorrect response the intensity of the stimulus is increased by a certain step), 75% of correct responses will be obtained. This sophisticated technique is called the 'up-down tracking response method' (UDTR method).

2.3.3.3.2 von Békésy method

Another variation of the method of limits is the von Békésy method. Békésy initially used the method with an audiometer to test hearing sensitivity, recording a continuous track of the stimulus intensity. Observers are presented continuous stimuli that gradually decrease or increase in intensity, they are asked to keep pressing a switch whenever they detect the stimulus, and to release the switch when it can no longer be detected. This procedure continues until performance becomes stable for some specified period of time has elapsed. The observer's tracking is often recorded and presented as in audiometry.

2.3.3.3.3 Magnitude estimation

The magnitude estimation procedure, a method of ratio scaling, devised by S.S. Stevens. This is a variation on the method of constant stimuli with a combination of scaling procedures; observers are required to make direct numerical estimations of sensory magnitudes provided by various stimuli. There are two main ways of applying the magnitude estimation technique to a scaling problem: (i) the observer is presented with a standard (reference) stimulus and told that the sensation it produces has a certain numerical value, such as 10. On subsequent trials, other stimuli are presented and the observer assigns numbers to sensations relative to the value of the standard; (ii) the standard value is not defined by the experimenter, the stimuli are randomly presented to the observer, who assigns numbers to sensations in proportion to their apparent magnitudes.

This method is suitable for determining the growth of sensation (see Section 2.3.4.3. Steven's power law) as a function of intensity at a number of different frequencies and also for establishing contours of equal subjective intensity (see Section 2.3.2.2.3).

2.3.4 Psychophysical Laws

One area of psychophysics concerns the formation of psychophysical laws representing how the intensities of stimuli and impressions of stimuli are related. The two contending laws are known as the logarithmic law and the power law.

2.3.4.1 Weber's law

The first psychophysical law was established by the German psychophysicist, G.T. Fechner (1801-1887). Sensations cannot be measured directly, and must be found by indirect means to relate sensory magnitudes to the physical intensities of the stimulus (Fechner, 1966, in reproduced version with translation). He believed the law proposed by E.H. Weber (1795-1878), the 'JND' (= difference threshold) in a stimulus magnitude is proportional to the magnitude of the stimulus. Although it was Fechner who established the law, he called it Weber's Law with respect for Weber:

$$\text{WEBER'S LAW:} \quad \Delta I \,/\, I = C$$

where I is the intensity of the stimulus, ΔI is the just detectable change, C is a constant. The fraction $\Delta I \,/\, I$ is often referred to as the "Weber fraction".

Weber's law indicates that the more intense the stimulus, the more the stimulus intensity has to be increased before a subject notices a change. In fact, it was later discovered that the percentage (JND) required is usually larger for stimuli close to threshold (after

Hawkins and Stevens, 1950). In order to widen its application, Weber's law can be revised slightly by the addition to the magnitude of the stimulus, S, a small constant, S_o:

$$JND = k(S+S_o)$$

2.3.4.2 Fechner's law

By making a number of further assumptions, Fechner generalised Weber's finding to express a broader relationship between sensory and physical magnitudes. The result was Fechner's law, which states that the strength of a sensation grows in proportion to the logarithm of stimulus intensity. The formula is given by:

$$\text{FECHNER'S LAW:} \qquad \psi = k \log \varphi$$

where ψ represents the psychological (subjective) magnitude, φ represents the stimulus intensity, and k is a constant that depends on the value of the Weber fraction. This law makes good biological sense, as our nervous system tends to have a logarithmic transformation mechanism.

2.3.4.3 Steven's power law

A new psychophysical law was developed by S.S. Stevens (1957) to replace of Fechner's logarithmic law. He proposed that the form of the relationship between sensation magnitude and stimulus intensity is a power function. The law is described as:

$$\text{STEVENS POWER LAW:} \qquad \psi = k \varphi^n$$

where ψ is the psychological magnitude in psychological units, φ is the stimulus magnitude in physical units, and n varies according to the sense modality in question. The value of the power function exponent determines the shape of the curve on a graph where the ψ is plotted as a function of φ. If the exponent is 1.0, the relationship is a straight line, in which sensory magnitude is proportional to stimulus intensity. The power function is a convenient feature for producing a linear function with a slope equal to the value of the power exponent when presented in log-log coordinates.

Although the effects of stimulus magnitude were less concerned in the present research (except for the Weber's law in Study 7), it is of interest whether the different power functions are obtained depending on receptor channel being excited.

2.4 PSYCHOPHYSICAL THEORIES FOR VIBRATION PERCEPTION

2.4.1 Duplex Theory

Psychophysical research enabled the definition of response functions for receptors responsible for the detection of vibratory stimuli. von Békésy (1939) initially investigated sensitivity to vibratory stimuli and introduced 'the flutter-vibration function': a U-shaped threshold curve as a function of frequency with the minimum value between 100 and 300 Hz (when plotted as a function of vibration displacement). These findings were similar to later results reported by Sherrick (1953).

There seemed to be two functionally distinct systems for the detection of vibration. Verrillo and co-workers intensively investigated the area in the 1960's and established the 'duplex model', in which the two separate systems were identified as Pacinian and non-Pacinian systems. The Pacinian system is mediated by FA II receptors and the non-Pacinian system includes the remaining receptors (i.e. FA I, SA I and SA II). The proposed duplex model is illustrated in Figure 2-7. The displacement threshold of the Pacinian system has a U-shaped frequency response. It was demonstrated that the sensitivity of the Pacinian system changes systematically (the U shape curve is shifted vertically, as shown in Figure 2-7) as functions of contact area (e.g. Verrillo, 1963, 1965) [Section 2.5.2.1], stimulus duration (e.g. Gescheider *et al.*, 1978; Green, 1977) [Section 2.5.1.3], skin temperature (e.g. Bolanowski and Verrillo, 1982) [Section 2.5.3.2] or the age of subjects (e.g. Verrillo, 1979a) [Section 2.5.4.1]. The horizontal broken line in the figure represents the threshold of the non-Pacinian system, being a displacement independent of frequency and incapable of sensitivity summation with the variables mentioned above. The flat response function appears when sufficient stimulus gradients were delivered to the skin, particularly with low frequency stimuli (Verrillo, 1979c). This duplex theory was later supported by findings of Gescheider (1976) who demonstrated absolute thresholds and sensation magnitudes for the receptors. The response properties of these receptor systems are summarised below (also see the data in Figure 2-8):

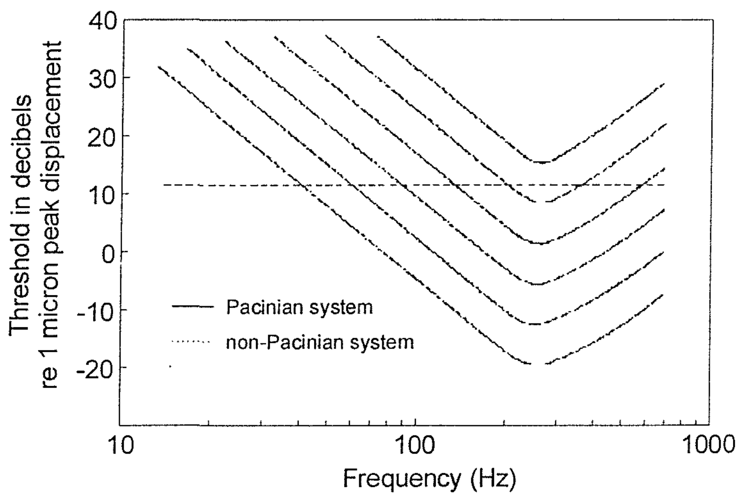


Figure 2-7 Duplex model of mechanoreception. (From Gescheider and Verrillo, 1978)

Sensitivity of **Pacinian system** increases with:

a)	increase in contact area	= 'spatial summation'
b)	increase in stimulus duration	= 'temporal summation'
c)	increase in skin temperature	= 'thermal effect'
d)	decrease in age	= 'aging effect'

Sensitivity of **non-Pacinian system** increases with:

e) increase in stimulus gradient = 'gradient effect*'

*Note that gradient effect can be produced by placing a surround around a contactor, which can be enhanced by a decrease in the gap between a contactor and a surround or an increase in the sharpness of a contactor edge (see further details in Section 2.5.2.3).

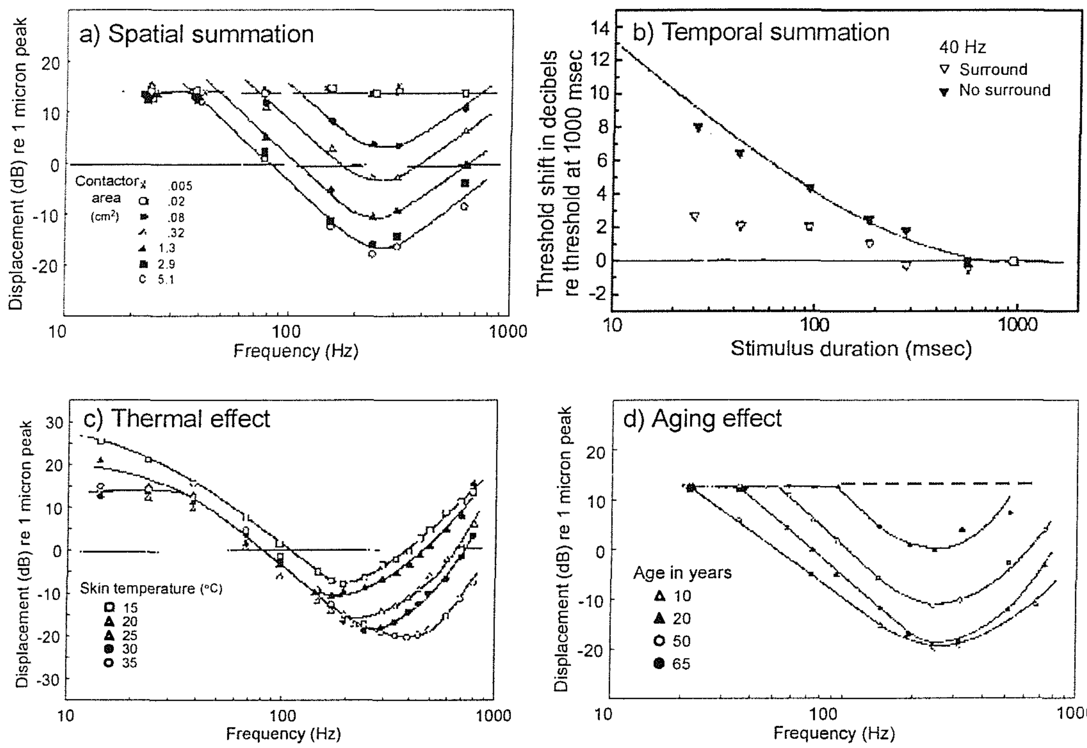


Figure 2-8 Evidence supporting the duplex theory. Change of Pacinian sensitivity is presented as a function of: (a) contact area (Figure from Verrillo, 1963); (b) stimulus duration (Figure from Gescheider *et al.* 1978); (c) skin temperature (Figure from Bolanowski and Verrillo, 1982); and (d) age (Figure from Verrillo, 1979a). The non-Pacinian system is represented by a horizontal line, which implies incapability of sensitivity summation.

2.4.2 Triplex Theory

There is an assumption in the last section that only two receptor systems detect vibration. Nevertheless, several investigations were made to find separate responses within the non-Pacinian system. Capraro *et al.* (1979) initially proposed a triplex theory of mechanoreception. They employed an adaptation stimulus (vibration exposure prior to the determination of thresholds) to separate the response of the NP system and also used a small contactor to eliminate the effects of the Pacinian system. It was found that a low-frequency adapting stimulus (10 Hz) elevated low-frequency thresholds more than high-frequency thresholds, which means the shape of the psychophysical threshold curve over the frequency range of 10-200 Hz was nearly flat before adaptation, but became negatively sloped after adaptation. Sub-threshold adaptation (= adaptation effects produced by levels of the adapting stimulus below its threshold) appeared only at low frequencies. It was suggested that there were responses from two receptors within the non-Pacinian system, namely the FA I and SA II receptors.

The triplex model (see Figure 2-9) was later produced by Gescheider *et al.* (1985) which was based on Capraro's results. The model was examined by Gescheider *et al.* (1985) employing forward masking to obtain independent responses from NP receptors (i.e. NP I and NP II) with a small contactor (0.01 cm^2) so that the Pacinian response was not obtained at the absolute thresholds. According to masking theory (see Section 2.4.4), masking only occur when the intensity of the masking stimulus is above the threshold of the same receptor system in which the test stimulus is detected. For example, the threshold for detecting a 15 Hz test stimulus should be elevated by a 15 Hz masking stimulus because both are detected by the NP I (FA I) channel. The threshold for a 40-, 63 and 100 Hz stimulus should also be increased by the 15 Hz masking stimulus. Then, the test threshold should increase as the masking stimulus intensity is increased only until the masked threshold at the test-stimulus frequency exceeds the threshold of the NP II (SA II) channel, which would be explained by the test and masking stimuli are detected by separate NP systems. If the model is correct, the masking functions for 40-, 63 and 100 Hz test stimuli should be unaffected by the presence of a 15 Hz masking stimulus. Experimentally measured masking functions were compared with masking functions predicted from the hypothesis that two NP receptor systems detect vibration stimuli, the results supported the hypothesis that the detection of vibration delivered through a small contactor is determined by two separate receptors of non-Pacinian system.

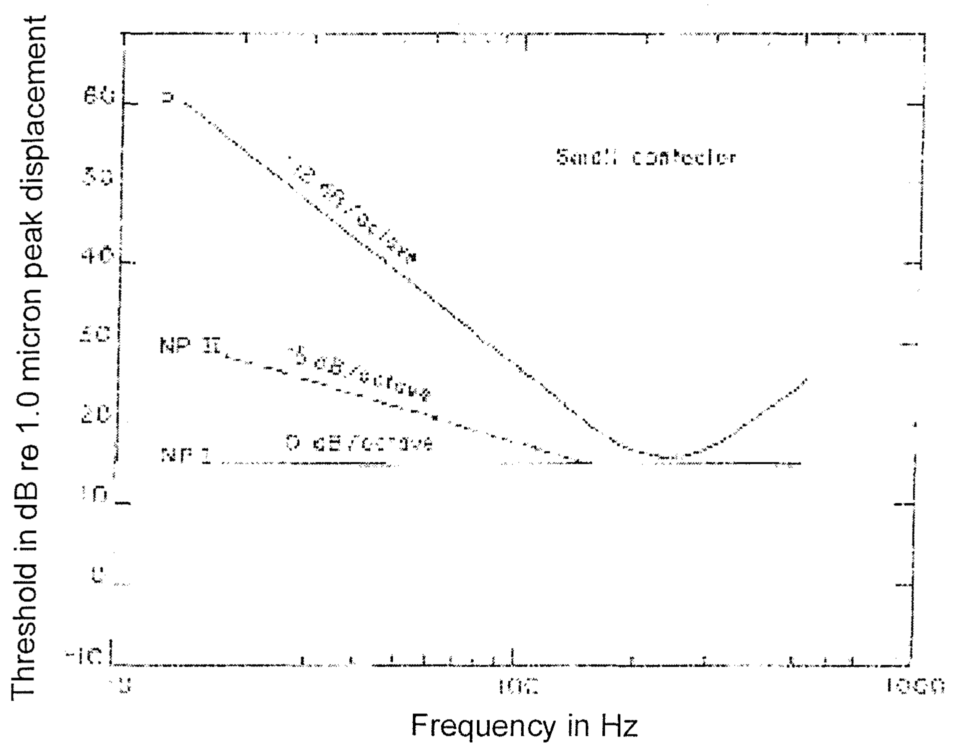


Figure 2-9 Triplex model of psychophysical thresholds for detection of vibration delivered through a small contactor (less than 0.02 cm^2) (the model is based on Capraro *et al.*, 1979)). The threshold of the Pacinian system (P) is too high to determine psychophysical thresholds at any frequency. Before adaptation, one non-Pacinian system (NPI) determines threshold at all frequencies. After low frequency adaptation the other non-Pacinian system (NP II) determines thresholds. (Figure from Gescheider, *et al.* 1985).

2.4.3 Four-channel Theory

Further investigation was made to identify the third receptor channel in the non-Pacinian system. Bolanowski *et al.* (1988) conducted a large study: (1) to determine absolute thresholds over a wide range of frequencies from 0.4 to 500 Hz using 0.008 cm^2 and 2.9 cm^2 contactors with a 1.0 mm gap. The examinations encompassed the effect of contactor size, skin temperature (15, 30 and 40 °C) and stimulus duration; (2) to determine masked thresholds using forward masking, applying a test frequency at 0.7 Hz with various masker frequencies (10, 20, 40, and 100 Hz). The results indicated that a third channel in the non-Pacinian system does indeed exist and operates in the vibratory frequency range between 0.4 and 100 Hz, and was identified with SA I receptors. The findings indicated that SA I displayed neither spatial summation nor temporal summation, and possibly no thermal effect. The four-channel model proposed by Bolanowski *et al.* (1988) is shown in Figure 2-10, each threshold curve has been compared with the neurophysiological thresholds and identified with the shape of psychophysical thresholds.

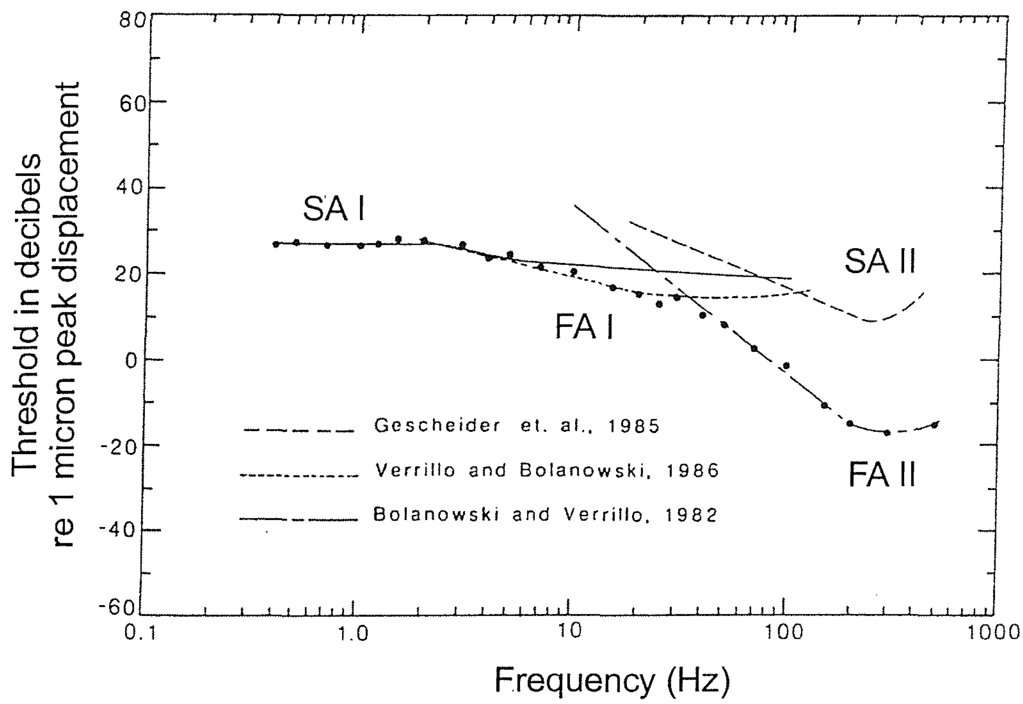


Figure 2-10 The four-channel model of vibrotaction showing the threshold frequency response function of each channel. (Figure from Bolanowski *et al.*, 1988)

2.4.4 Masking Theory in Vibrotaction

Recent studies on masked thresholds for vibration stimuli have revealed a unique response feature that masking occurred only when the masker and test stimulus excited the same receptor system (e.g. Gescheider *et al.*, 1982, 1983, 1985; Hamer, 1979; Hamer *et al.*, 1983; Verrillo *et al.*, 1983), which leads the hypothesis that neural activities of Pacinian receptors can mask the detection of a test stimulus by the same receptors, but cannot mask the detection of a test stimulus by non Pacinian receptors, or vice versa.

According to this masking theory, the masking function can be predicted if the thresholds of each receptor is presented. Figure 2-11 is an illustration of prediction technique produced by Gescheider *et al.*, (1982). Above N, there is a range *A* of maskerintensities where both masker and test stimuli are mediated by Pacinian system. The masking intensity will elevate threshold of test stimulus until the test stimulus begin to be mediated by non-Pacinian system. *P* will be obtained until the masker begins to excite the non-Pacinian system, to be able to mask the test stimuli shown as *B*. This elaborated technique could also be applied in an opposite way: the threshold curve of each receptor can be determined once knowing the masking functions.

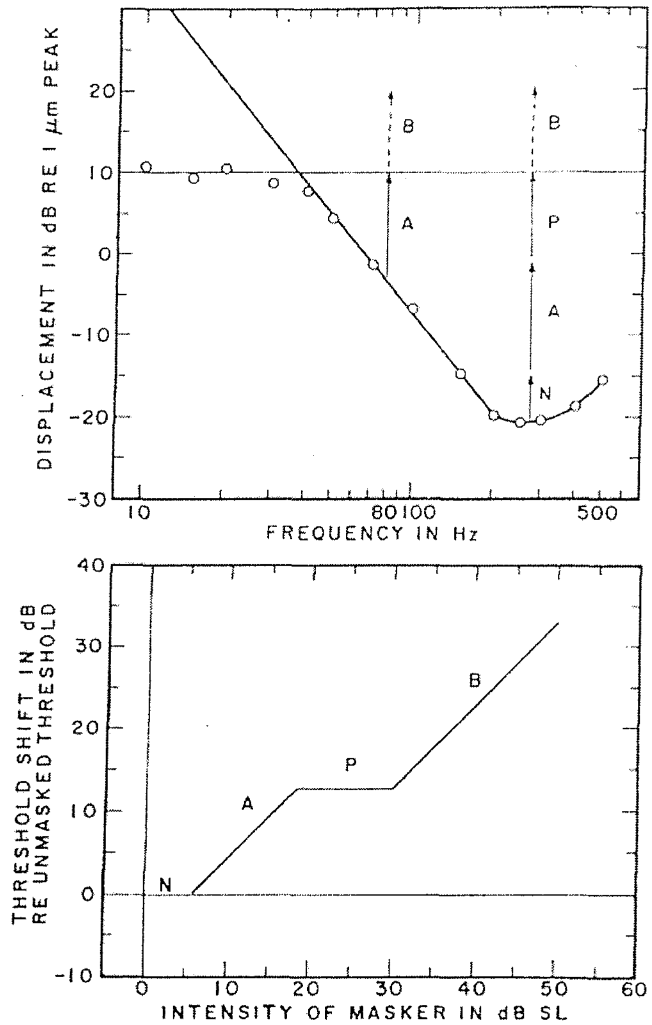


Figure 2-11 Illustration of how the masking function for the 80 Hz test stimulus with a masker of 275 Hz centred narrow-band noise was predicted. The masking function in the lower half of the figure is predicted from the threshold function above it. (Figure from Gescheider *et al.*, 1982)

2.5 FACTORS AFFECTING PERCEPTION FOR HAND-TRANSMITTED VIBRATION

One of the major problems in the field of sensory psychology has been the specification and the control of the stimulus. For vibration stimuli, Griffin (1990) has defined three areas of variability that contribute to the cause-effect relationship of human responses to vibration: the nature of the vibration, the characteristics of the exposed persons, and the environment. Figure 2-12 shows a schematic model of the cause-effect relationship for perception of hand-transmitted vibration based on Griffin's model. For perception of hand-transmitted vibration there is a particular variable, the skin-stimulus contact, which is known to have a large influence on perception. This section is concerned with factors affecting the perception of hand-transmitted vibration: the available literature was assembled and is summarised systematically.

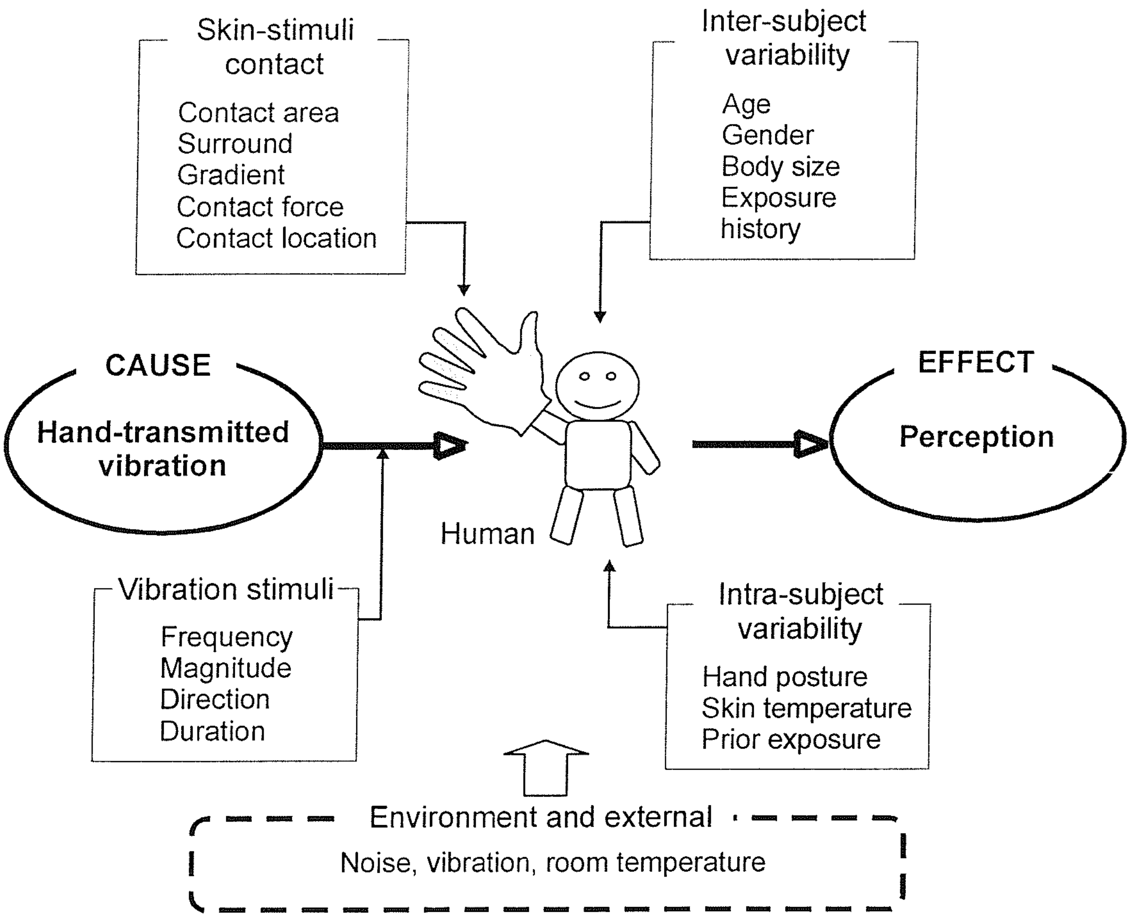


Figure 2-12 A schematic presentation of the relation between factors influencing perception of hand-transmitted vibration.

2.5.1 Vibration Stimuli

2.5.1.1 Stimulus frequency

Studies of vibration perception must consider the frequency response functions. Indeed, a large number of researches in perception of hand-transmitted vibration have presented threshold contours as a function of frequency within the frequency range from 0.4 up to 1200 Hz. It became evident that different frequencies of the stimulus excites different receptors, and each receptor has distinctive frequency response functions. The U-shaped frequency dependence of absolute thresholds at high frequency (the most sensitive frequency being 200 to 300 Hz, when the magnitude of vibration is expressed in displacement) have been found in most studies and are nowadays well known as the response mediated via the Pacinian system (e.g. Verrillo, 1966a, 1966b, 1968). Horizontal (i.e. flat, frequency independent) functions at low frequencies, below about 40 Hz (when expressed as displacements) for perception mediated via the non-Pacinian system has also been demonstrated (e.g. Verrillo 1966b, 1968; Gescheider *et al.*, 1978) (see duplex theory, Section 2.4.1). However, this does not

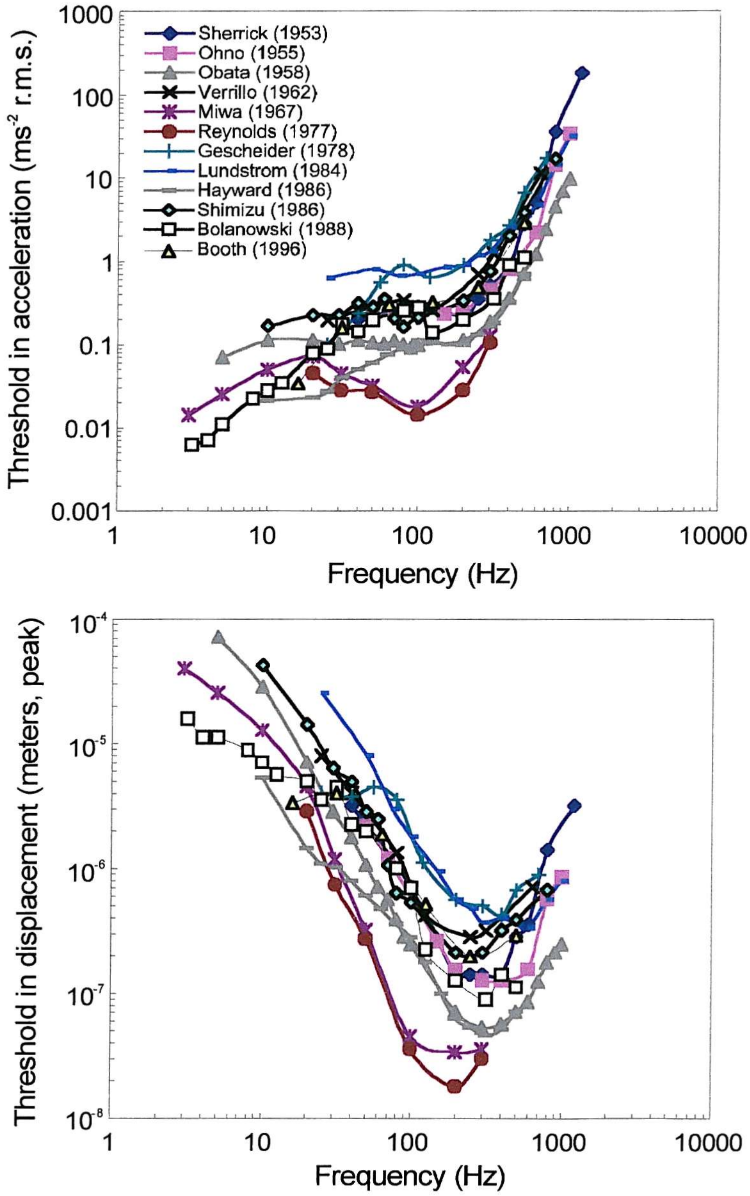


Figure 2-13 Absolute threshold contours obtained from independent studies. The measurement conditions corresponding to each set of threshold data are listed in Appendix E.

imply that these frequency functions obtained from studies are comparable to each other. Figure 2-13 displays frequency functions of absolute thresholds assembled from selected studies so as to make some rough comparison of threshold contours between studies. To ease the comparison of the threshold data, they are expressed as functions of both acceleration and displacement. The corresponding measurement conditions for each curve are shown in Appendix E.

As can be seen in Figure 2-13, a variety of threshold contours were obtained over the frequency range from 3 to 1200 Hz in the different studies. Roughly similar shapes were observed with the same frequency dependence. With acceleration scales, thresholds are generally high at high frequency (above 150-200 Hz) and low at low frequency (below 50 Hz). Curiously, thresholds measured with the whole-hand (e.g. Miwa 1967, Reynolds *et al.* 1977) are different in shape from those measured at the fingertip. These thresholds are considerably lower than thresholds at the fingertip, at around 100-150 Hz. They apparently fall at frequencies around 100 Hz. With displacement scales, the U-shaped curves appear to be lowest at about 200-300 Hz. Surprisingly, although similar shapes are seen in the studies, the difference in threshold levels is about 20 dB, or more! The threshold differences are apparently due to the different measurement conditions employed in different studies; however, it is not possible to identify the factors causing these differences in Figure 2-13.

2.5.1.2 Stimulus magnitude

Suppose the stimulus magnitude increases by a factor of two, one might assume that the sensation of observers would also double. However, sensitivity to vibration may not vary in this way, the sensation increment may depend on the stimulus and other factors.

Stevens (1959a,b, 1968) investigated the growth of sensation caused by vibration stimuli at the fingertip, determining the value of the exponent at different frequencies (see Steven's power law in Section 2.3.4.3) using the methods of magnitude estimation and cross modality matching. Figure 2-14 shows equal sensation functions for different frequencies of vibration, illustrating how the exponent of the power function for vibrotaction changes as a function of stimulus frequency from 15 to 250 Hz. It was found that the exponent for 60 Hz stimulus was not far from 1.0, the exponent decreased at lower frequencies and increased at higher frequencies: 1.17, 1.2, 0.8, and 0.67 for the frequencies shown in Figure 2-14. Similar results are reported by Franzén (1969) who used similar measurement conditions. However, slightly inconsistent results were obtained in a study by Verrillo *et al.* (1969) and Verrillo (1970), finding no effect of frequency and an exponent of 0.89. Verrillo and Capraro (1975) found that removal of a surround caused independent of frequency in the slope of the curve, it was assumed to be due to the change of total activity of different receptors.

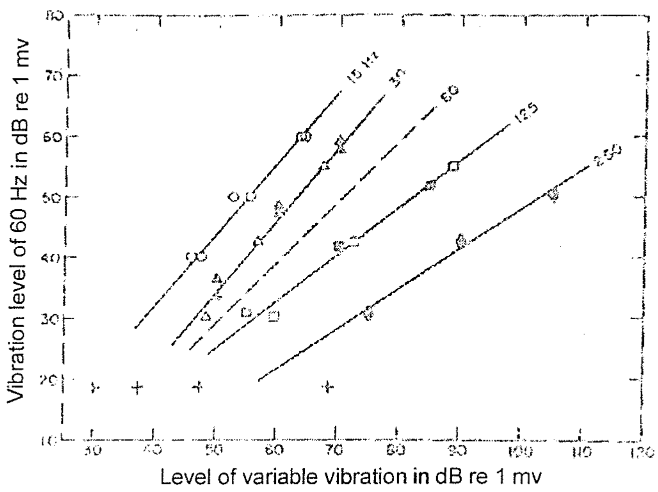


Figure 2-14 Matching functions between 60 Hz vibration and other frequencies applied at the fingertip with no surround. (Figure from Stevens, 1968)

A study by Gescheider (1976) examined temporal summation via the Pacinian system. It was demonstrated that there were separate sensation magnitude functions for Pacinian and non-Pacinian systems, as seen in Figure 2-15. The dependence on duration became less with higher magnitudes. Another interesting finding was that the function was a 'double power function', with exponents of approximately 1.0 for weak stimuli and 0.5 for strong stimuli, the critical point for changing the exponent value is about 20 dB above the threshold level, which might be due to the combination of response by the Pacinian and non-Pacinian systems.

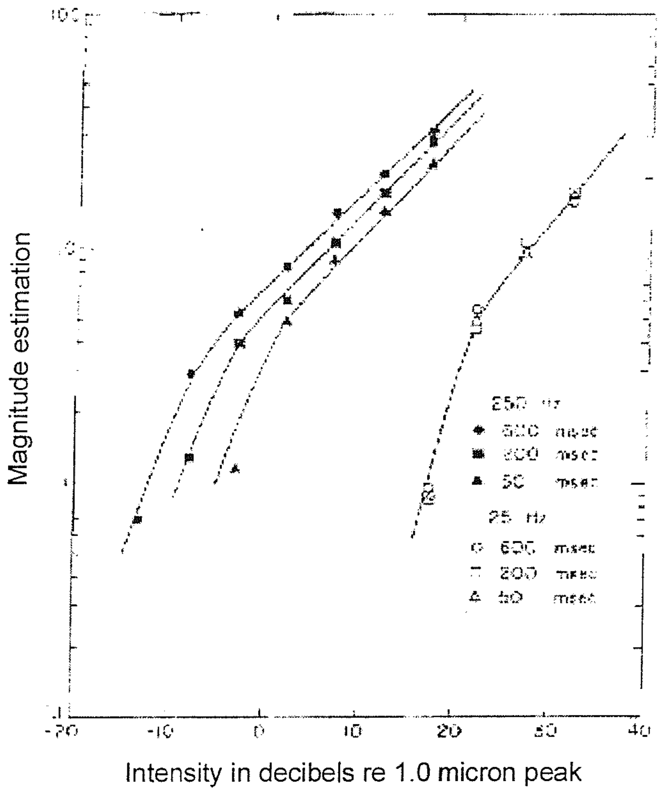


Figure 2-15 Magnitude estimation as a function of the intensity with 25 and 250 Hz applied at the thenar eminence, 3.0 cm^2 contactor, 1.0 mm surround gap. (Figure from Gescheider, 1976).

2.5.1.3 Stimulus duration

Variations in the duration of the vibration stimulus also alter the sensation. Zwislocki (1960) initially proposed a model for the process of temporal summation of auditory stimuli, in which there was a decrease in the absolute threshold of sensation with increasing stimulus duration. Verrillo (1965) investigated the temporal summation theory with vibrotactile stimuli, determining vibrotactile thresholds as a function of the burst duration of sinusoidal signals varying from 10 to 1000 milliseconds. He also examining the effect of the repetition rate of short pulses and the number of pulses. The burst duration effect is shown in Figure 2-16. The theory predicts a decrease in thresholds at the rate of 3 dB per doubling of burst duration, up to about 60 milliseconds. It was suggested that temporal summation was only exhibited via the Pacinian system: the effect of stimulus duration was obtained with high frequencies, with the removal of the surround (see effect of surround, Section 2.5.2.2.1) and also with larger contact areas (Pacinian system also displays spatial summation, see Section 2.5.2.1). These findings were used to support duplex theory by Verrillo (1968) and Gescheider (1976) (see Section 2.4.1). This temporal summation was assumed to be due to exciting more receptors, which might be recruited by energy increment as suggested by Leshowits and Raab (1966). Checkosky and Bolanowski (1992) obtained consistent results from a combination of physiological and psychophysical measurements, which were summarised in terms of low-amplitude, long-duration stimuli producing neural events in Pacinian corpuscles equivalent to those produced by high-amplitude, short-duration stimuli.

With hand-transmitted vibration using a handle grasping posture, Maeda (1986) determined magnitude estimations with varying durations (0.4 to 40 seconds) of white noise vibration stimuli. It was observed that the subjects tended to make a greater judgement as the duration of the stimuli increased.

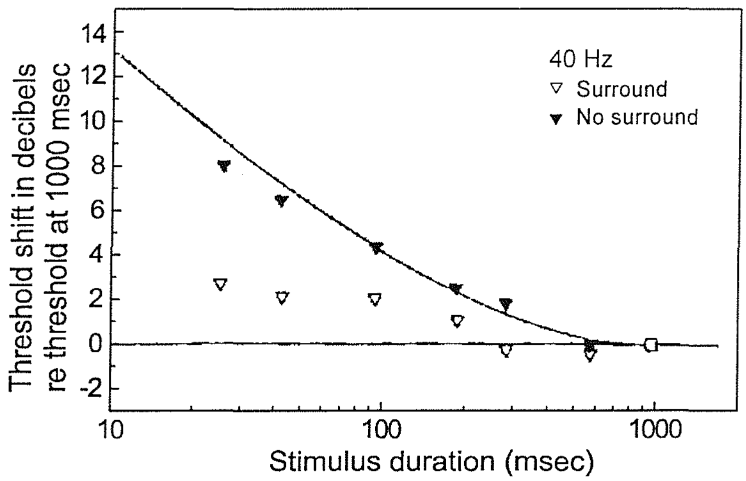


Figure 2-16 Effect of duration of vibration stimuli; vibrotactile threshold shift as a function of burst duration at three frequencies. (Figure from Gescheider, 1978)

2.5.1.4 *Stimulus direction*

A majority of threshold measurements have involved solely vertical vibration. Shimizu and Ooishi (1986) determined absolute thresholds at the fingertip (contact area about 150 mm^2) in the vertical and horizontal directions (achieved by altering the position of the fingertip over the shaker) in the frequency range 10 to 800 Hz and found no significant difference between the two directions above 30 Hz.

With hand-transmitted vibration, Miwa (1967) determined absolute thresholds and equal sensation contours, and observed similar thresholds levels between vertical and horizontal axes. Mishoe and Suggs (1974) compared equal sensations caused by sinusoidal and non-sinusoidal vibration in both a single direction and in three directions over the range 32 to 2000 Hz. The results showed that sensations increased with increasing spectral content and increased with additional axes of vibration, especially at low frequencies. Reynolds *et al.* (1977) also determined absolute thresholds and equal sensation contours with three directions. In his results there seem to be indications that sensation may be influenced by the direction of the stimulus.

The current International Standard for measuring, evaluating and assessing the hand-transmitted vibration (i.e. ISO 5349-1, 1996) provides only a single frequency weighting for all three directions, assuming there is no dependence on stimulus direction. Griffin (1997) commented, "a different weighting should be applied to each of the axes before their effects are compared or combined".

2.5.2 Skin-stimuli Contact Variability

2.5.2.1 *Contact area*

Contact with the skin surface cannot be neglected as a factor influencing sensation, because there will be no sensation without contact of the skin with a vibrating surface. Verrillo (1963) investigated the effect of contact area and determined vibrotactile thresholds as a function of frequency with various contactor configurations, and also as a function of contact area applying various sizes of contactor from 0.005 to 5.1 cm^2, while holding a constant gap with a surround at 1.0 mm. The results are shown in Figure 2-17, together with the corresponding full sized contactors in Figure 2-18, so as to make realistic comparisons. The striking findings include: (i) increases in sensitivity by approximately 3 dB per doubling of contact area at frequencies above 40 Hz; (ii) no change in sensitivity below 40 Hz with increasing contact area; (iii) independence of contactor size and frequency with very small contact areas (e.g. 0.005 and 0.02 cm^2). The effect was later proposed as 'spatial summation' mediated by the Pacinian system (Verrillo 1966b, 1985). This spatial summation effect became one of the response properties of the Pacinian system used to support the duplex model.

Spatial summation provided an 'issue' for further investigation: whether static force contributed to spatial summation (Craig and Sherrick, 1969; Green and Craig, 1974), whether multiple areas of stimulation can also produce spatial summation (Craig, 1968; Franzen *et al.* 1970; Muijser, 1994), and whether spatial summation is influenced by the presence of masking stimuli (Craig 1976).

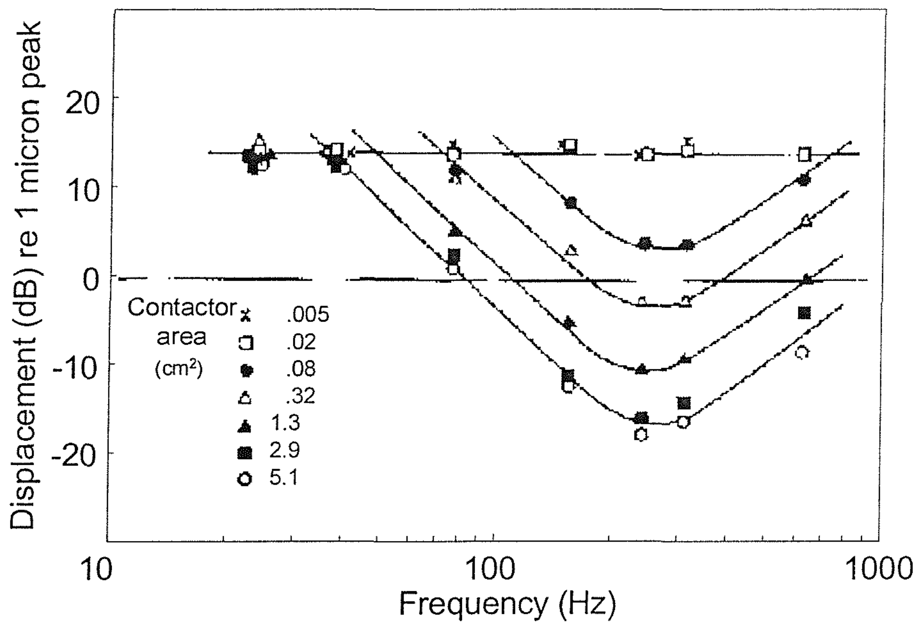


Figure 2-17 Effect of contact area on vibrotactile thresholds of detection for sinusoids measured at the thenar eminence of the right hand. Figure from Verrillo (1963).

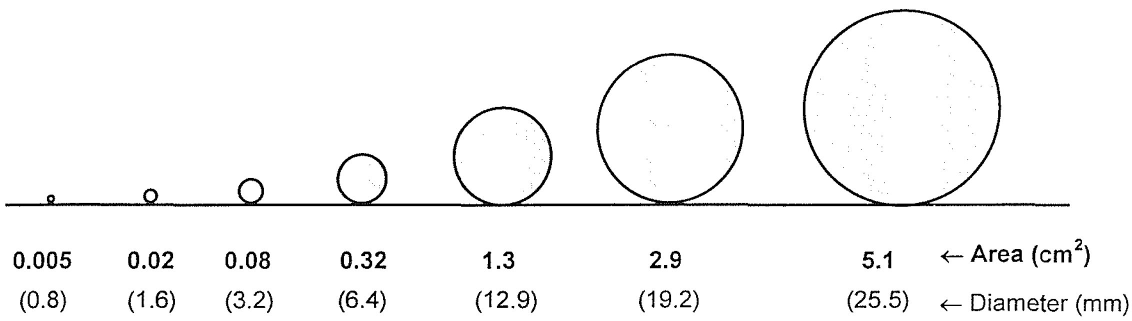


Figure 2-18 Contactor sizes corresponding to the experimental results of Verrillo (1963) (see Figure 2-17). (Approximately full sized)

For hand-transmitted vibration, Maeda and Iwata (1984) determined equal sensation contours with three different sizes of handle (i.e. 25, 30, 35 mm in diameter) over the frequency range from 10 to 250 Hz. Lower sensitivity was somewhat obtained with the larger size of the handle.

It was thought by the present author, it is possibly due to the change in gripping force caused by the change in handle size, rather than due to the change in contact area. It seems contact force is an independent factor influencing sensitivity of perception, in addition to contact area (see Section 2.5.2.4).

2.5.2.2 Surround

The form of the relationship between the vibrotactile threshold and stimulus frequency seems to be strongly influenced by whether or not a rigid surround is applied. This was initially discovered in a study by Verrillo (1962), in which two frequency response functions (horizontal line and U-shaped curve) were only observed when a rigid surround was present; if the rigid surround was not used or if there was a large gap between the surround and the contactor, the threshold function was often found to be a U-shape over the entire frequency range, with no appearance of a horizontal flat line at low frequencies.

The effect of a surround on vibrotactile perception was later investigated by simply comparing absolute thresholds with and without a surround. An elegant demonstration was made by Gescheider *et al.* (1978), applying two different contact areas (0.2 and 3.0 cm^2) in conjunction with the presence and absence of a surround. The findings included: (i) removal of the surround affected the flat part of the response function; (ii) removal of surround reduced the amount of spatial summation. Figure 2-19 shows one of the results. These were explained by: (i) removal of the surround allows vibration to spread across the surface of the skin, which provides a similar situation of spatial

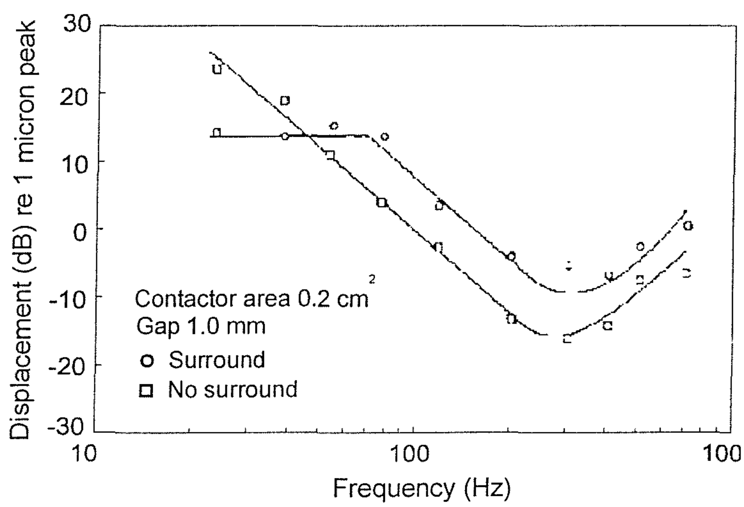


Figure 2-19 Effect of surround determined at the thenar eminence. (Figure from Gescheider *et al.*,1978).

summation and increases sensitivity via the Pacinian system; (ii) the surround excites gradient stimuli which increase the sensitivity of the non-Pacinian system. The effect of the surround has also been examined in several other studies with consistent results, although with different contact conditions: 1.4, 7.0 and 25.4 mm diameter contactors with 1 mm gap and with no surround (Goble *et al.,* 1996); 7.0 mm diameter contactor with 1.5 mm gap, 3.0 mm gap and with no surround (Harada and Griffin, 1991); 1.5 cm^2 contactor with 5.0 cm diameter surround and with no surround (Lamoré and Keemink, 1988); 0.72 cm^2 contactor with 1.0 mm gap and with no surround (van Doren, 1990).

Since evidence of the effect of a surround was discovered, the use of a surround became popular, with two main purposes: (i) to confine areas of vibration so as to control the area responding via the Pacinian system; (ii) to provide gradient stimuli on the skin surface in order to enhance responses via the non-Pacinian system. This technique is extremely useful for research involving the identification of receptor channels, and is often used in masking experiments.

2.5.2.3 Stimulus gradients

It was explained in the previous section on the effect of a surround, that the presence of a surround produces stimulus gradients to excite the non-Pacinian system. Extra attention has been paid to this gradient effect since Verrillo (1962, 1963) and Gescheider *et al.* (1978) hypothesised that the edge of a contactor may also produce the surface gradient mediated by the non-Pacinian channel. Verrillo (1979c) examined the effect of gap distance between a surround and a contactor (from 1.0 to 15.0 mm), the edge surface of the surround (varying sharp, rounded, and no

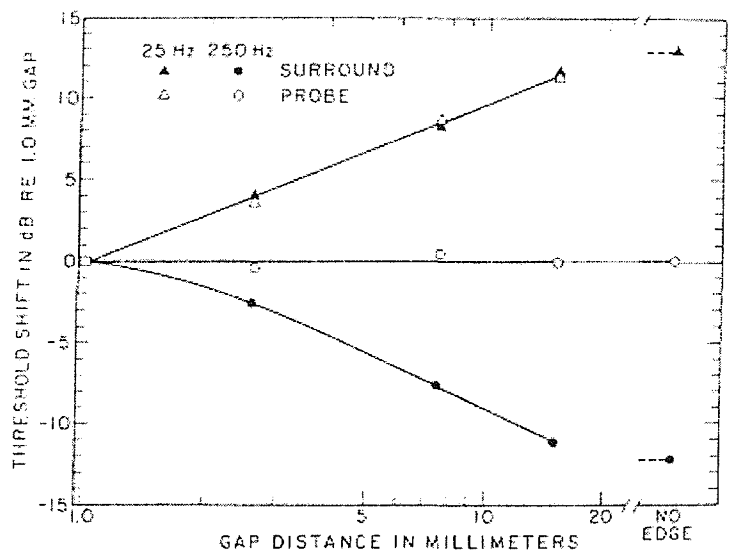


Figure 2-20 Threshold shift as a function of gap distance, referred to a gap distance of 1.0 mm. 0.32 cm^2 contactor, 0.005 cm^2 prove. (Figure from Verrillo, 1985)

edge) and an extra probe. One of the remarkable findings was the effect of gap distance: an increase in gap distance decreased thresholds at low frequencies; in contrast, increases in gap distance increased thresholds at high frequencies. It seems that the Pacinian and the non-Pacinian responses were affected simultaneously by altering of gap distance. Diminished gradients were obtained from rounded edges, which resulted in higher thresholds by approximately 3 dB than with normal edges, at 25 Hz. It was suggested that the stimulus gradients are mediated by the non-Pacinian systems, which provided further evidences in support of the duplex model established by Verrillo (1968).

2.5.2.4 Contact force

Craig and co-authors investigated the factors influencing spatial summation demonstrated by Verrillo (1962). Craig and Sherrick (1969) initially pointed out that Verrillo (1962) chose to hold constant the contactor penetration while increasing the area of the contactor, which apparently produced an increase in the static force as well as an increase in pressure. An experiment was undertaken to investigate whether spatial summation at threshold is different when force, penetration or pressure were held constant. Three different stimulus frequencies at 20, 80 and 250 Hz were used with three different contact areas: 3.25, 15.7, 66.3 mm^2. The remarkable findings were that: (i) holding contactor penetration constant with a doubling of contact area decreased thresholds at high frequency (250 Hz) by about 3 dB; (ii) doubling contact force increased sensation magnitudes by approximately 3 dB; (iii) there was no increase in sensation magnitude with increase of contact area when holding the stimulus magnitude and contact pressure constant. Green and Craig (1974) further approached this matter, determining equal sensation magnitudes using two different contact areas: 0.07 and 1.24 cm^2. The results indicated that an increase in perceived magnitude was obtained by increasing static force without changing contact area at low frequencies (25 and 40 Hz) as well as at high frequency (160 Hz). A decrease in vibrotactile thresholds with increasing contact force (or static indentation) has been confirmed by Harada and Griffin (1991), Lamoré and Keemink (1988), Lindsell (1997) and Makous *et al.* (1996b), the effect was found to be greater with high frequency than with low frequency stimuli. Consistent results were also obtained by Lowenthal and Hockaday (1987) and, moreover, it was reported that the effect was more marked in diabetic peripheral neuropathy. However, no information was provided on which frequency of vibration stimuli was applied.

Considering the force produced from the whole hand contact, Thonnard (1997) hypothesised that the grasping forces may be different according to the task in use of vibrating tools, and the manipulation skill will be reduced due to exposure of hand-transmitted vibration. He observed the pressure perception, vibration perception and manipulative skills with a task of grip lift movement after the 30 minutes of vibration exposure at 3.2 m/s^2.

The above findings from the studies seem to suggest that force affects sensation more for the Pacinian system than the non-Pacinian system, however it remains uncertainty whether this is due to the spread of the mechanical stimulus over a larger area or whether the stimulus is more efficiently mediated by receptors when the force is greater.

2.5.2.5 Contact location

2.5.2.5.1 Variations over the body

Gregg (1951) determined vibrotactile thresholds for various body areas at 120 Hz. The fingertips were found to be the sensitive points and the range of maximum to minimum sensitivity was about 46:1.

A comprehensive study by Wilska (1954) measured vibrotactile thresholds over the frequency range 25 to 1250 Hz, applying a 1cm^2 probe over the whole body area (34 points). It was found that the most sensitive frequency range was between 200 and 250 Hz (when expressed in displacement) and the sensitivity levels depended on the body area. The results at 200 Hz are shown in Figure 2-21. Absolute thresholds varied from –23 dB (= about 0.04 ms^{-2} r.m.s.) at the fingers

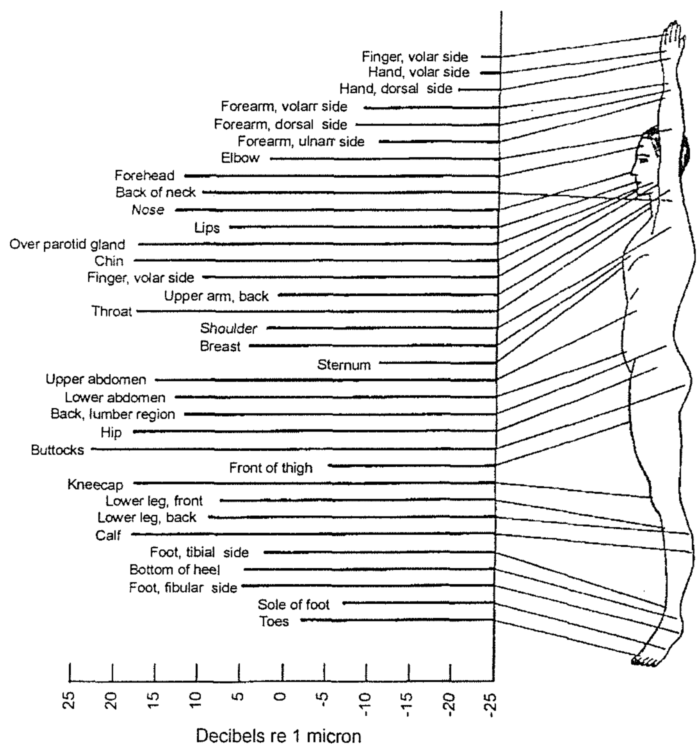


Figure 2-21 Bodily distribution of vibratory sensitivity. Thresholds, in decibels of 34 skin areas at 200 Hz. From the data of Wilska (1954).

to +23 dB (= about 8.0 ms^{-2} r.m.s.) at the buttocks.

2.5.2.5.2 Hairy and non-hairy skin

Verrillo (1966c) determined thresholds on the hairy skin of the volar forearm and compared the threshold contours with his earlier data at the thenar eminence (Verrillo, 1963). As seen in Figure 2-22, the difference in sensitivity between the two sites was more than 10 dB, with less sensitive thresholds at the non-hairy skin area. The two threshold curves were almost identical to each other so it was concluded that the same types of receptors (possibly FA I and FA II) were innervating the two sites.

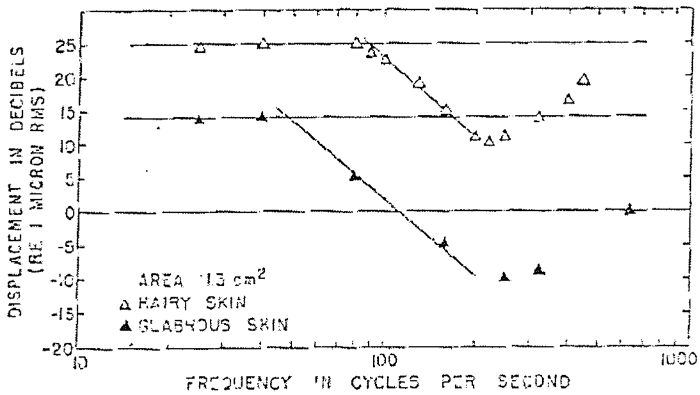


Figure 2-22 Vibrotactile thresholds on hairy and glabrous skin for a contact area of 1.3 cm^2. Figure from Verrillo (1966c).

Unique and rather useful studies have been made by determining tactile sensitivity on the tongue (Fucci *et al.*, 1972, 1984; Green, 1987; van Boven and Johnson, 1994; Verrillo, 1966d), these are mainly to obtain the response functions of receptors other than Pacinian corpuscles (It is generally agreed that the tongue contains no Pacinian corpuscles.). The findings from Verrillo (1966d) confirmed the duplex theory that no spatial or temporal summation is produced in the absence of Pacinian corpuscles measured at the tongue.

2.5.2.5.3 Glabrous areas of the hand

Further investigation has been carried out to examine whether the sensations depend on location on the glabrous areas of the hand. Roland and Nielsen (1980) determined absolute thresholds for 100 Hz vibration at eight different points over the glabrous hand using a 13 mm diameter contactor. Löfvenberg and Johansson (1984) also measured absolute thresholds with a 6 mm diameter contactor at seven points. Lundström (1984a) conducted a similar study with a 9 mm diameter contactor over 15 different points (see

Figure 2-23). These findings did not find conclusive, significant or consistent differences between the tested points. This is may have been due to the absence of a surround resulting in spatial summation over wide and undefined areas via Pacinian receptors: a surround would have confined the stimulus area to points close to the contact area and also encouraged excitation by non-Pacinian receptors (Section 2.5.2.2). Booth (1996) determined vibrotactile thresholds at four different locations over the frequency range from 16 to 500 Hz with a surround. The results are illustrated in Figure 2-24, it is seen that differences in threshold were obtained between the hand area and the wrist area. The fingertip was found to be the most sensitive area at low frequencies, but there was no difference in sensation at high frequencies when compared with the thenar eminence. No differences in threshold were obtained between the inner and outer wrist, which might suggest that variation sensitivity is more significant between locations than between skin types (hairy or non-hairy skin) as shown by Verrillo (1966c) (Section 2.5.2.5.2).

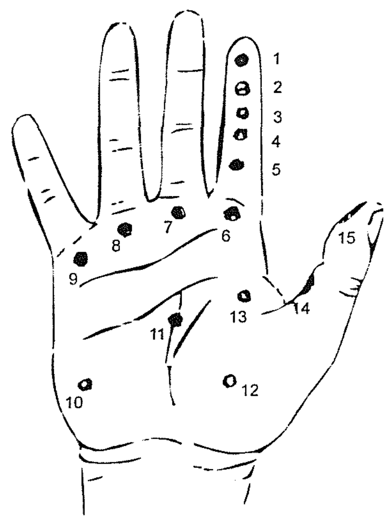


Figure 2-23 Fifteen test points on the glabrous skin of the hand by Lundström (1984a).

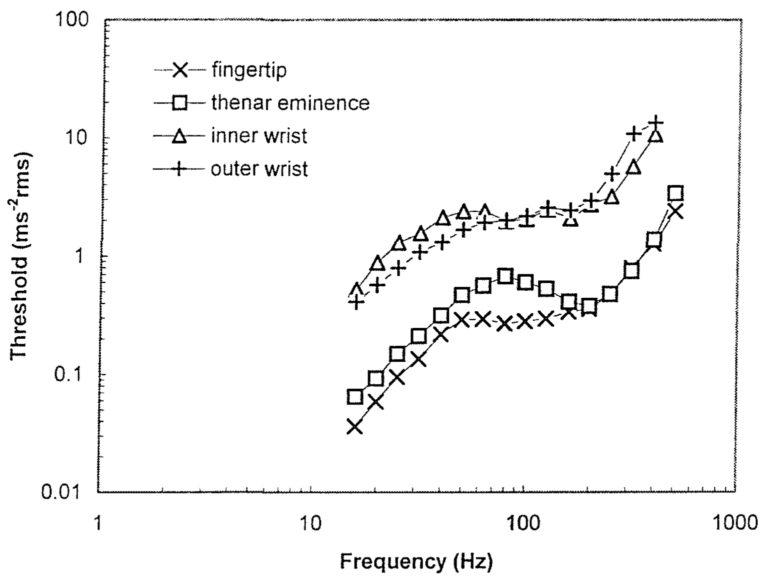


Figure 2-24 Vibrotactile thresholds determined with four different locations using 6 mm diameter contactor with a 10 mm diameter surround. Data reproduced from Booth (1996).

2.5.3 Intra-subject Variability

2.5.3.1 Hand/finger posture/orientation

When operating vibrating tools, it is often impossible to be exposed without altering hand posture or hand orientation. Changing posture could be a factor influencing sensations, although there are few studies investigating this. Obata (1958), in a series of studies, exposed himself with seven different finger contact conditions involving different directions of vibration stimuli. In each condition he determined absolute thresholds and a critical frequency where the observer feels a change in sensation. Slight differences in the shapes of the threshold contours due to altering postures were observed, although there was no consistent pattern.

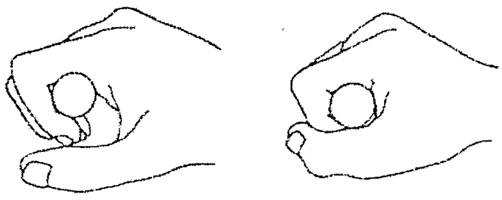


Figure 2-25 Two types of handle-gripping posture: (A) Finger grip (B); Palm grip. Figure from Reynolds and Keith (1977).

Reynolds et al. (1977) chose two different handle grip postures (see Figure 2-25) to determine absolute thresholds and sensation magnitudes. The results seemed to show no difference in sensation between the postures. However, posture differences might cause some change in grip forces which might result in altered sensation due to the change in impedance at the hand.

2.5.3.2 Skin temperature

Skin temperature is known to affect vibrotactile thresholds. An elegant demonstration was made by Bolanowski and Verrillo (1982): vibrotactile thresholds were determined both psychophysically and neurophysiologically over the frequency range 15 to 800 Hz at the thenar eminence with varying skin temperatures between 15 and 43 °C. The mean threshold contours from the psychophysical study are shown in Figure 2-26. The thresholds tend to increase with decreasing skin temperature, which was significant at high frequencies. There was little change in thresholds at temperatures between 29 and 41 °C. Similar results were obtained from other psychophysical studies by Harada and Griffin (1991) and Green (1977), both observing a curious phenomenon: a decrease in sensitivity (elevation of thresholds) with further increases in temperature above 35 °C.

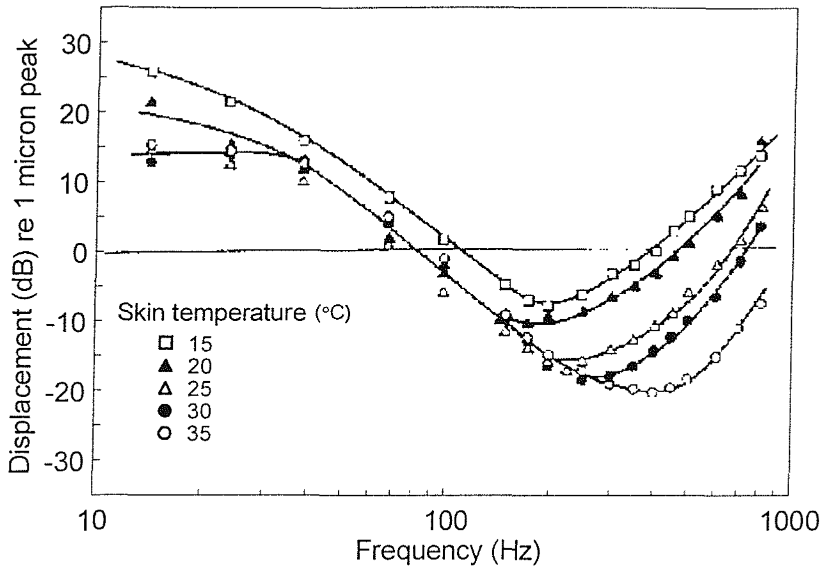


Figure 2-26 Effect of skin temperature on vibrotactile thresholds. Contactor area 2.9 cm^2, 1.0 mm gap. Figure from Bolanowski and Verrillo (1982).

Hayward and Griffin (1986) reported a variation in vibrotactile sensitivity (at 63 and 125 Hz) with skin temperature among VWF subjects. It has been suggested that the sensitivity of Pacinian receptors is dependent on skin temperature (Bolanowski and Verrillo, 1982; Harada and Griffin, 1991; Green 1977).

A further investigation was undertaken by Verrillo and Bolanowski (1986), using a smaller contact area (0.0008 cm^2) to minimise the Pacinian responses while applying contact at the thenar eminence and the volar forearm so as to obtain thresholds with and without the Meissner's responses. A dependence on skin temperature was only seen at the forearm (below 100 Hz), suggesting that either SA I or SA II receptors responded to the stimuli.

The effect of skin temperature has also been examined with supra-threshold vibration stimuli. Gescheider *et al.* (1997), determined difference thresholds at 250 Hz with a 3.0 cm^2 contactor applied to the thenar eminence. Although detection thresholds were substantially higher at 20 °C than at 30 or 40 °C, the relative difference thresholds (Weber's fraction, $\Delta I/I$) were more or less independent of the skin temperature.

2.5.3.3 Prior exposure to hand-transmitted vibration

Extensive studies have investigated the effects of vibration on thresholds, particularly aiming to define work-shifts for occupational tool users so as to minimise risks of peripheral disorders (e.g. vibration-induced white finger). It became evident that exposure to hand-transmitted vibration can cause a temporary reduction in the normal sense of touch (temporary threshold shift = TTS).

A large number of researches have employed the measurement of vibrotactile thresholds prior to and after exposure to hand-transmitted vibration in order to assess the relationship between TTS and the characteristics of vibration exposure. Various types of vibration exposure have been investigated: (i) sinusoidal vibration (e.g. Harada, 1978a,b; Harada and Griffin, 1991; Hayward, 1984; Nishiyama and Watanabe, 1981; Lundström, 1986; Lundström and Johansson, 1986); (ii) spectral, octave- or composite-band vibration (e.g. Maeda and Kume, 1987, 1989; Nishiyama *et al.*, 1996); (iii) intermittent vibration (e.g. Maeda and Kume, 1991); repetitive shock type vibration (e.g. Maeda and Griffin, 1993); (iv) vibratory tools (e.g. Bovenzi *et al.*,1997; Maeda, 1995; Thonnard *et al.*, 1997). It was noted that many of these studies (except Bovenzi *et al.*, 1997; Harada and Griffin, 1991; Lundström, 1986; Lundström and Johansson, 1986) determined vibrotactile thresholds only at high frequencies (i.e. above 64 Hz), which implies the stimulus was mediated by Pacinian receptors, considering the contact conditions employed (i.e. contactor area, surround, see Section 2.5.2.1 and 2.5.2.2).

A comprehensive study by Harada and Griffin (1991) demonstrated TTS in vibrotactile thresholds at frequencies of 16 to 500 Hz induced by 5-minute exposures of the hand to vibration at 20 ms^{-2} r.m.s. with discrete frequencies from 16 to 500 Hz. The TTS at 0.5 minutes ($TTS_{0.5}$) was calculated from the measurements and is shown in Figure 2-27. It is seen that the vibrotactile thresholds were mostly affected by the same range of frequencies in the exposure stimulus: *vibration exposure at high* frequencies (i.e. 125, 250 and 500 Hz) most elevated the vibrotactile thresholds at high frequencies; conversely, vibration exposure at low frequencies (i.e. 16, 31.5 and 63 Hz) most elevated the vibrotactile thresholds at low frequencies. However, it was noted that exposure to vibration at low frequencies also *induced significant TTS in the* vibration thresholds at high frequencies.

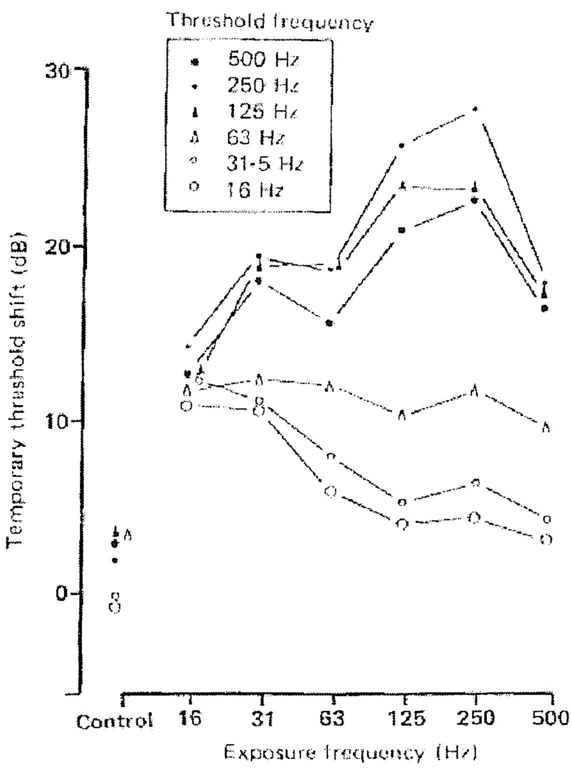


Figure 2-27 $TTS_{0.5}$ of the vibration sense threshold of the fingertip. Figure from Harada and Griffin (1991).

Bovenzi *et al.* (1997) examined vibrotactile thresholds at 16, 31.5 and 125 Hz before and after exposure to vibration from impact wrenches operated by 30 workers. The frequency characteristics of the tool were dominant at high frequencies. It was found that low frequency thresholds were less affected compared with the high frequency thresholds.

These findings can partly be explained by a psychophysical study undertaken by Verrillo and Gescheider (1977), determining vibrotactile thresholds at 25 to 250 Hz before or after conditioning stimulation of 10 Hz. Results showed that the low frequency thresholds increased proportionally by increasing conditioning stimulation of a low frequency signal, while there was little effect on high frequency thresholds.

Lundström and Johansson (1986) reported that pre-exposure at a particular frequency caused an acute depression of the sensitivity of mechanoreceptive afferent units which are mostly sensitive in the frequency range of the stimulation. However, as commented by Lundström (1986), it can be expected that all types of mechanoreceptors will often be affected, particularly with high magnitudes of vibration, due to an overlap in the frequency ranges of the mechanoreceptive afferent units.

2.5.4 Inter-subject Variability

2.5.4.1 Age

It is no doubt that the sensitivity of all sensory systems diminishes in function with advancing age (e.g., hearing loss). The tactile senses are no exception; many studies have documented an association of vibrotactile thresholds with age (e.g. Bartlett *et al.*, 1998; Era *et al.*, 1986; Gerr and Lets, 1993, Hong *et al.*, 1994; Liou *et al.*, 1999; Lundström *et al.*, 1992; Wild *et al.*, 1999). It is appeared to be true that the loss of sensitivity with advancing age is not uniform across frequencies of vibration. Goff *et al.* (1965) found that detection thresholds at high frequencies were most affected. Verrillo (1979a) determined the vibrotactile thresholds in five age groups from 10 to 65 years. It was reported that there is a progressive decrease in sensitivity with age at high frequencies but no change at low frequencies (see Figure 2-28). A similar aging effect on vibrotactile thresholds has been reported in several studies (Bolanowski *et al.*, 1988; Frisina and Gescheider, 1977; Goble *et al.*, 1996; Verrillo, 1977, 1979a). It has been later suggested that the P channel (Pacinian corpuscle) becomes less sensitive with aging, while the NP channels (RA, SAI and SAII) are unaffected (Gescheider *et al.* 1996a; Verrillo 1980).

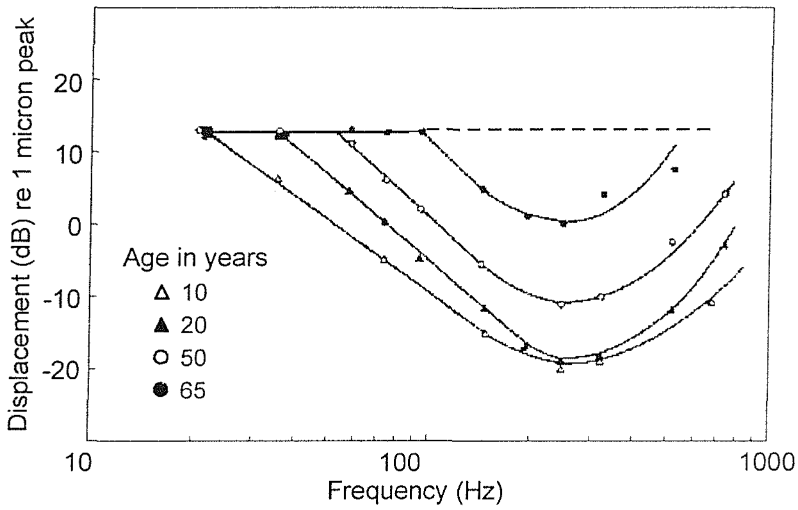


Figure 2-28 Effect of age on vibrotactile thresholds. Figure from Verrillo (1979a)

The perception of supra-threshold tactile stimuli is also affected by aging. Verrillo (1982) determined the sensation magnitudes of stimuli of equal vibration amplitudes using magnitude estimation, and found the contour of the P channel was lower in older subjects than in younger subjects. However, the intensities of stimuli presented to each subject were specified relative to a subject's detection threshold rather than as absolute intensities, thus the detection abilities of the older and younger subjects were essentially the same.

The aging effect was further examined in several studies, as 'enhancement', in which there is an increment in the subjective magnitude of one stimulus due to the presentation of a prior stimulus (Verrillo, 1982), gap-detection (van Doren *et al.*, 1990), forward masking (Gescheider *et al.*, 1992). It was generally suggested that the Pacinian system is most influenced by aging.

2.5.4.2 Body size

A correlation between vibrotactile thresholds and height is somewhat notable. A significant increase in thresholds with increasing height was found by Gerr and Lets (1994), who measured 120 Hz thresholds at the index finger and the great toe, and by Era *et al.*, (1986), who measured at the inner malleolus (i.e. a round bony projection) of the ankle. Sosenko *et al* (1989) tested on diabetic patients and reported a significant association between height and thresholds at toe, but not those at finger. Gadia *et al.* (1987) also found on diabetic patients, there were strong associations of vibration sensitivity with height, while no relation was obtained between thermal sensitivity and height.

Verrillo (1977) suggested that the elevation of vibrotactile thresholds from 10 to 23 years of age is at least partly due to the increase in the size of the hand, which leads to a less dense distribution of the receptors. The effect of height is possibly due to differences in impulse conduction in the afferents, which are also longer in taller subjects, especially from the distal parts of the body. Motor nerve-conduction velocities have been shown to be related to height in normal subjects (Soudmand *et al.*, 1982). Another explanation could be a less dense distribution of the mechanoreceptors on the larger body surfaces of taller subjects.

2.5.4.3 Gender

Gender effect on vibrotactile thresholds is appeared to be present, indeed some studies reported that the female subjects were found to be more sensitive to vibration stimuli than the male subjects (Bergenheim *et al.*, 1992; Frenette *et al.*, 1990; Hiltz *et al*, 1998; Maser *et al.*, 1997) although some studies did not find significant correlation with sex (Hong, 1994; Liou *et al.*, 1999; Bartlett *et al.*, 1998; Sosenko et al., 1989; Verrillo, 1979b). Interestingly, it seems that gender was confounding the relationship between height and threshold, as males are generally taller than females. Bergenheim *et al.* (1992) and Maser *et al.* (1997) reported that gender differences disappeared when sensory thresholds were normalised for height, this can be explained by increased neuron length, which has been discussed earlier (see Section 2.5.4.2).

Nevertheless, it is still possible to consider that gender may be a factor of influencing neural sensitivity. Gescheider *et al.* (1984) examined in several experiments looking at the effects of menstrual cycle on vibrotactile sensitivity, determining psychophysical thresholds with low frequency and high frequency vibration (15 and 250 Hz) at the thenar eminence of the hand at various times in the menstrual cycle. The results were compared with male subjects and also female subjects who took birth control pills. It was found that males and females differed in sensitivity to only high-frequency vibration; it appears that women were no more sensitive than men in detecting vibration during the onset of menstruation. It was suggested that the presence of one or both of the female hormones, progesterone and oestrogen, have the effect of increasing the sensitivity of the Pacinian system, but not of the non-Pacinian system.

2.5.5 Other Variables

2.5.5.1 Ingestion

2.5.5.1.1 Alcohol and nicotine consumption

A large cross-sectional epidemiological study by Geer and Lets (1994) investigated covariates of sensory thresholds (i.e. vibrotactile at 120 Hz and thermal thresholds) measured from the index finger and great toe of 4,462 male subjects. The examination included smoking status (current non-smoker or smoker) and alcohol-drinking status (five categories). An absence of adverse effect of alcohol consumption on sensory thresholds was found. A small positive effect of smoking was observed for great toe vibrotactile thresholds, but not for finger vibrotactile thresholds.

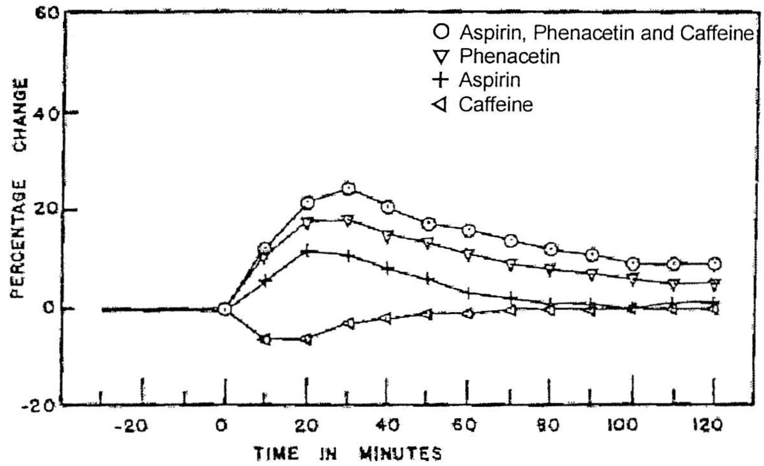


Figure 2-29 Average response in 50 subjects. The deviations from the line shown for pre-ingestion times were negligible. Figure from Gregg (1952).

2.5.5.1.2 Drugs and supplements intake

Gregg (1952) investigated the effect of drugs on vibrotactile thresholds, examining combinations of three different drugs which were compounded with the following weights of active ingredients: 1) 195 mgm. of aspirin, 2) 15 mgm. of caffeine, 3) 195 mgm. of aspirin plus 180 mgm. of phenacetin, and 4) 195 mgm. of aspirin plus 180 mgm. of phenacetin plus 15 mgm. of caffeine. The summary results are shown in Figure 2-29, indicating that combinations of drugs produced changes in responses rather than single drug ingestion. A unique effect was obtained with caffeine, which produced negative responses, although it contributed to positive responses when it was mixed with the other drugs. The effective duration was immediately after the ingestion and for up to 120 minutes, although it depended on the maximum response. Due to the lack of information at which frequency of stimuli thresholds were tested, it is not certain which receptor was influenced by ingestion of drugs.

An interesting observation of some relationships of the vibratory sense to vitamin levels and vitamin usage were made by Whanger and Wang (1974), in which subjects who were taking vitamin supplements which did not contain vitamin B_{12} had markedly elevated thresholds over both those taking no vitamin supplements at all or those taking supplements containing vitamin B_{12}. It should be noted that the measurements were made with acutely admitted and chronically hospitalised elderly psychiatric patients (over 65 years).

2.5.5.2 Psychophysical algorithm

There seems to have been very little attention to how vibration perception obtained by one psychophysical algorithm differs from that obtained by another algorithm. Researches tend to rely on the measured sensation as an 'absolute' value. However, uncovering the response properties of mechanoreceptors from the literature, the method of stimulation seems to have a great influence on the mediation of the receptor systems, which may produce 'relative' values. Different techniques for measuring sensory thresholds involve different types of stimulation (i.e. intermittent or continuous stimulation). The different stimulation may bias the neural activity of mechanoreceptors because it is known that sensation is influenced by stimulus duration (see Section 2.5.1.3). Involving long exposures may also cause an acute depression of mechanoreceptors sensitivity (see Section 2.5.3.3).

2.6 SUMMARY

Throughout this chapter, the 'pieces' have been put together so as to work out the puzzle of the 'tactile mechanisms'.

The perception of vibration at the glabrous skin of the hand seems to reflect the response properties of several mechanoreceptors (i.e. FA I, FA II, SA I and SA II) (Section 2.2.2.1). Each receptor has distinctive functions in the mediation of vibration stimuli, so as to provide us with a complex pattern of sensations (Section 2.2.2.2). Two separate systems (i.e. Pacinian and non-Pacinian systems) have been clearly identified in psychophysical investigations (Section 2.4.1), although some studies have demonstrated independent receptors in the non-Pacinian system (i.e. FA I, SA I and SA II), suggesting triplex theory (Section 2.4.2) and four-channel theory (Section 2.4.3).

The Pacinian system (i.e. FA II) is found to play a large role in responses; it is most sensitive to vibration stimuli at high frequency, being capable of energy summation over contact area (= spatial summation, Section 2.5.2.1) and stimulus duration (= temporal summation, Section 2.5.1.3). A systematic increase in sensitivity was also found with increase in skin temperature and increase in contact force (Section 2.5.2.4). Additional influential factors are aging (Section 2.5.4.1) and, possibly, gender (Section 2.5.4.3). The non-Pacinian system (i.e. FA I, SA I and SA II receptors) is responsible for the perception of low frequency stimuli and has a particular response feature with being sensitive to stimulus gradients (Section 2.5.2.3).

Surround and contactor size appear to be critical factors influencing the sensitivity of both the Pacinian and the non-Pacinian systems. The presence of a surround around a contactor provides a sufficient gradient to enhance the function the non-Pacinian system, whereas the absence of surround permits enlargement of the stimulated area due to lateral spread of vibration over the skin, resulting in lower thresholds due to spatial summation via the Pacinian system (Section 2.5.2.2). Larger contactor areas make the Pacinian system more sensitive, whereas very small contactor areas (i.e. less than 0.02 cm^2) enhance responses via the non-Pacinian system (Section 2.5.2.1).

There remains uncertainty related to the perception of vibration in the whole hand. The available studies in the area are isolated, with few links to the known mechanisms of the receptor systems developed from investigations of localised areas of the glabrous skin. Comparisons of absolute thresholds in separate studies of the fingertip and the whole hand (Section 2.5.1.1) might imply some difference in sensitivity, although it is impossible to identify either the reasons for any differences or the implications, due to the large variations in experimental conditions between the studies. Contact with the whole hand on a vibrating surface may give a complicated contact condition: force may be produced in several ways, pushing (or pulling) and gripping a handle, which may vary with the manipulation tasks of tools, involving varied hand orientations and postures (Section 2.5.2.4 and Section 2.5.3.1).

A careful choice of psychophysical method seems necessary to obtain quantitative and meaningful results (Section 2.5.5.2). The current draft of International Standard (ISO/FDIS 13091-1, 2001) identifies possible methods of measuring vibrotactile thresholds at the fingertips. However, no particular method has been agreed for general use, probably due to the lack of evidence on how the psychophysical method influences the measured threshold.

Many more 'pieces' remain to be fixed in the 'puzzle': the laboratory studies reported in this thesis were shaped to fill some of the gaps.

2.7 SUGGESTIONS FOR DESIGNING EXPERIMENTAL CONDITIONS

This literature review has enabled to identify known variables and factors influencing detection sensitivity to vibration stimuli, which produced some suggestions for designing laboratory studies in the present research; there seem some need to be taken into account so as to minimise the unwanted effects when testing hypotheses.

This research was mainly objected to explore how the perception of hand-transmitted vibration depends on vibration stimulus and other variables on normal subjects, not testing normative data of thresholds. It is therefore become apparent that intra- and inter- subject variability should be controlled in the present studies:

- Skin temperature is well known factor (Section 2.5.3.2) affecting measured thresholds, it is therefore sensible to make a criterion of subjects' skin temperature, which shall be above 29 °C to avoid unwanted effect.
- Prior exposure to vibration stimulus can elevate their sensory thresholds, temporary as well as permanently (Section 2.5.3.3). Subjects who have not been exposed to severe or long period of vibration at their hands should only be eligible for testing. It is also important to make sure experimental session contains enough pause between tests so that measured thresholds are not affected by the previous test.
- Age is seemed to give relatively large effect on sensitivity to vibration (Section 2.5.4.1), which suggested to limit in younger group of subjects with smaller age differences (i.e. 20-29 years).
- Height rather than gender appeared to be a significant factor, however, there may be another explanation of gender effect (Sections 2.5.4.2. and 2.5.4.3), so it was chosen to exclude females for the subjects in the present research.
- As ingestions (i.e. drugs, alcohol, smoking, supplements) are known to affect measured sensory thresholds (positively as well as in negatively) (Section 2.5.5.1), which suggests that subjects should not be allowed to consume any of above, at least 2 hours before testing.

CHAPTER 3

APPARATUS AND VIBRATION MEASUREMENT

3.1 INTRODUCTION

This chapter describes the apparatus used for the laboratory studies and the methods employed for measuring vibration.

3.2 APPARATUS

Three different set ups (A, B and C) were used, depending on the measurement conditions of the study and are illustrated in Figure 3-1. The equipment used for each study is summarised in Table 3-1.

Table 3-1 Apparatus used for each laboratory study (The set up type A, B, and C correspond to the hardware layout illustrated in Figure 3-1.)

Study number	Set up	Vibrator	Accelerometer type	Force cell type	Computer/software type	Masking noise
1	B	Vibrometer		None	IBM P133	None
	C	Vibrometer		None	Hi-Grade #0	
2	A	VP 4	B&K 4371	Kulite	IBM P90	60 dB(A)
	B	Vibrometer		None		
3	B	Vibrometer		-	IBM P133	
4	C	Vibrometer		-	Hi-Grade #0	None
5	A	VP 30	DJ Birchall A/20T	DS Europe	Hi-Grade #16 486/66	None
6	A	VP 30	DJ Birchall A/20T	DS Europe	Hi-Grade #16 486/66	None
7	A	VP 4	DJ Birchall A/20T	Kulite	IBM P90	70 dB(A)
8	A	VP 30	DJ Birchall	DS Europe	Hi-Grade #16 486/66	65 dB(A)
	B	Vibrometer				

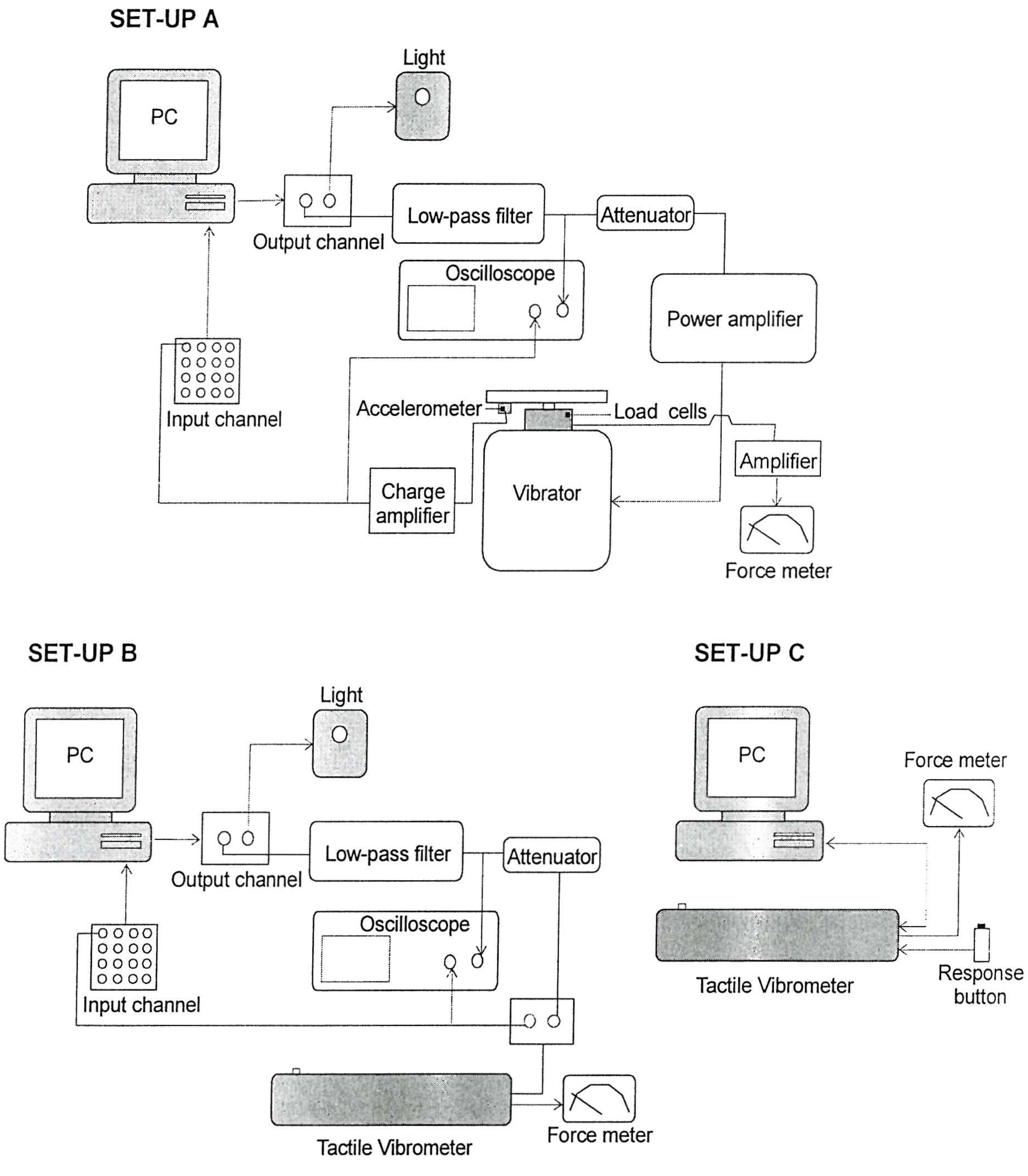


Figure 3-1 Layout of equipment used for the laboratory studies

3.2.1 Vibrators

3.2.1.1 HVLab Tactile Vibrometer

The *HVLab* Tactile Vibrometer is in-house developed hardware, which was designed to enable the measurement of vibrotactile perception thresholds for use in medical, industrial and laboratory research. It consisted of a power supply unit, a vibrometer unit, a force meter and a subject response button (optional).

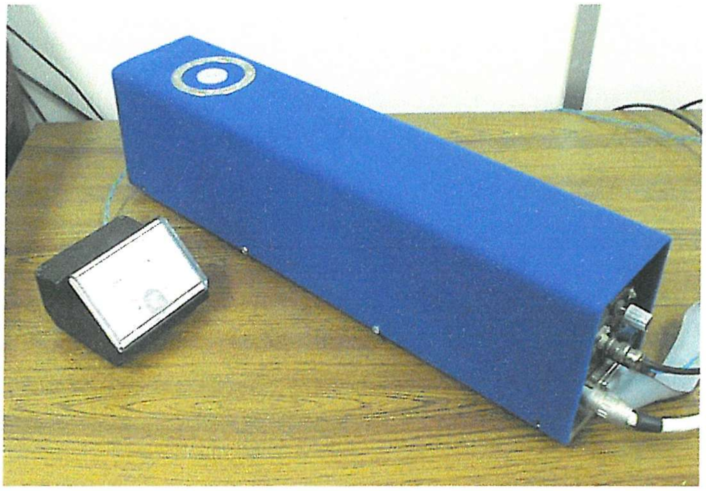


Figure 3-2 Exterior view of the Tactile Vibrometer

Vibrotactile thresholds can be determined using the *HVLab* Tactile Vibrometer. The Vibrometer unit contains an electrodynamic mini-shaker (Ling V101) attached via an accelerometer (PC308 B14) to a 6 mm-diameter nylon probe. The probe is counter-balanced to produce a constant upward force and protrudes through a 10 mm-diameter hole in a flat plate. Strain gauges are mounted under the plate to indicate the downward push force. A meter was provided for visual feedback of the force applied by the finger. A schematic view of the Vibrometer is shown in Figure 3-3, and the skin-stimulator contact conditions are summarised in Table 3-2.

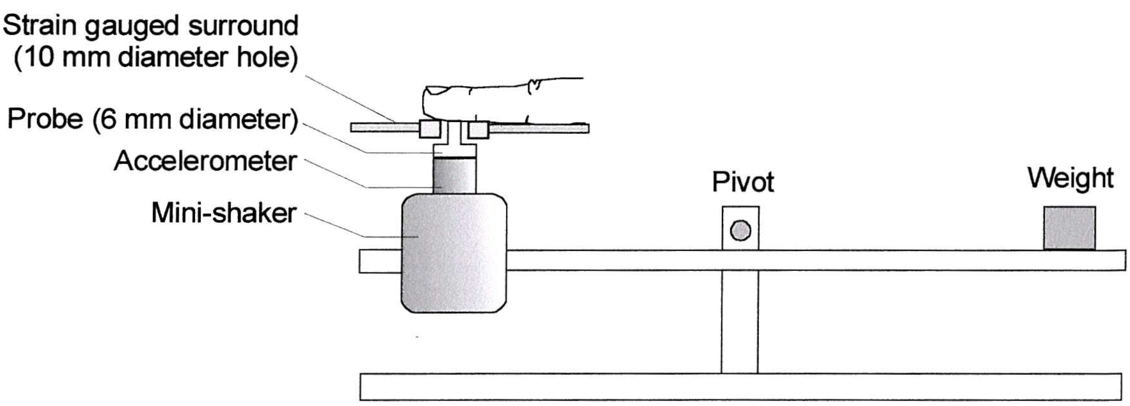


Figure 3-3 Schematic view of the Vibrometer unit

Table 3-2 Skin-stimulator contact conditions of *HVLab* Tactile Vibrometer

Probe diameter	6 mm
Probe-surround gap	2 mm
Contact force	1 N
Push force	2 N
Skin indentation	2.78 mm *

* data from Lindsell (1997)

3.2.1.2 Electrodynamic vibrator

Derritron VP 4 (permanent magnetic field)

The VP 4 (see Figure 3-4) has a suspension system consisting of three flexible spiders, one each at the top and bottom of the a.c. drive coil, and one attached to the top of the drive table. The vibrator supports a static load of 1.8 kg. A trunnion was not used with the vibrator. The dimension and size of the vibrator are:

Height: 260 mm
Width: 337 mm
Table: 70 mm in diameter
(9 inserts M6 × 12 deep)
Mass: 45.5 kg, 100 lb

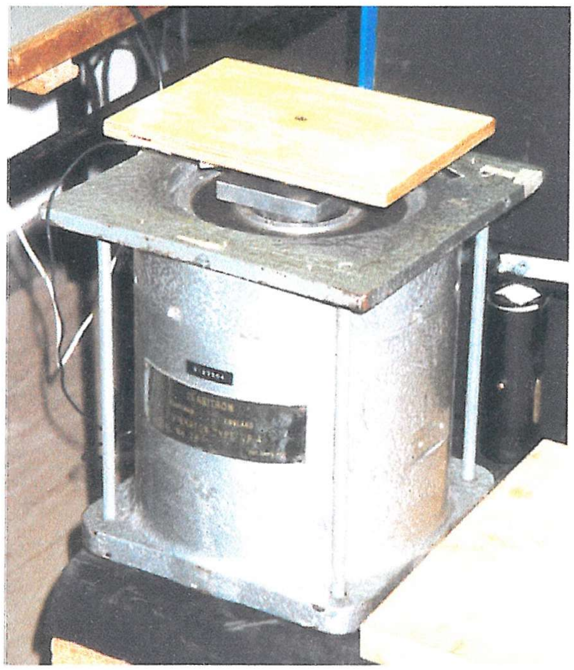


Figure 3-4 Exterior view of the VP 4 vibrator with a force cell and a wooden plate at the top.

The VP 4 vibrator was powered by a 100 watt amplifier. The performance of the vibrator system with this amplifier was not available but, with a similar amplifier (Derritron TA120), the performance is provided below for reference:

Peak sine vector force:	133 N	13.6kgf
Randon r.m.s. force:	53 N	5.4 kgf
Maximum acceleration:	309 m/s^2	
Maximum velocity:	1.27 m/s	
Maximum displacement (peak-peak):	6.35 mm	

Derritron VP 30 (electromagnetic field)

The VP 30 (see Figure 3-5) has a three-link arm suspension system that supports a static load of 22.7 kg. The vibrator was mounted in a rigid trunnion. The dimension and size of the vibrator are:

Height:	508 mm (with a trunnion)
Width:	368 mm (vibrator only) 546 mm (with a trunnion)
Table:	146 mm in diameter (9 inserts tapped M6 × 10 deep)
Mass:	182 kg, 401 lb (vibrator only) 291 kg, 641 lb (vibrator and trunnion)

Figure 3-5 Exterior view of the VP 30 vibrator with a force cell and a wooden plate at the top.

The VP 30 vibrator was powered by a 300 watt amplifier (type Derritron TA300), supplied with a cooling fan (model 9MS8). The performance details of the vibrator system are:

Peak sine vector force:	890 N	90 kgf
Randon r.m.s. force:	342 N	35 kgf
Maximum acceleration:	392 m/s^2	
Maximum velocity:	0.7 m/s	
Maximum displacement (peak-peak):	11.5 mm	

3.2.2 Transducers

3.2.2.1 Accelerometer

When using the electrodynamic vibrator (either VP4 or VP30), the vibration stimuli were monitored using a piezoelectric accelerometer attached on (or beneath) the contactor surface. The accelerometer employed in the research was either from Brüel and Kjær (type 4371) or DJ Birchall (type, A20/T). The signals from the accelerometers were passes through a charge amplifier (Brüel and Kjær, type 2635).

3.2.2.2 Load cells

A load cell (force transducer) was mounted on the electrodynamic vibrator, to monitor the constant contact force of a subjects' hand during the measurement of thresholds. Two types of load cell were employed:

Kulite load cell (type S 2000 500)

- 50 mm in diameter, 25mm of height, 10 mm of threaded hole at the centre
- Output 0.9 mV

DS Europe (type LT-05A5)

- 78 mm in diameter, 27 mm of height, 10 mm of threaded hole at the centre.
- Maximum load at 10 kg, Sensitivity 2mV/V FS

The output indicating force was provided to a force meter via an amplifier so that subjects could monitor their applied forces during a test.

Figure 3-6 Exterior view of load cells: left (Kulite) right (DS Europe).

3.2.3 Vibration generation and data acquisition

Acceleration signals were generated and acquired using a personal computer. Two types of software were used for the perception measurements.

3.2.3.1 HVLab Tactile Vibrometer software

The *HVLab* Tactile Vibrometer hardware can be controlled by the *HVLab* Tactile Vibrometer software (version 3.0) via a personal computer fitted with an Avantech PCL812-PG interface card for analogue-to-digital and digital-to-analogue conversion. The software was designed for measuring vibrotactile thresholds with a fixed procedure, the up-and-down method of limits (von Békésy method). It is capable of producing a sinusoidal vibration stimulus in the frequency range 16 to 500 Hz. Vibration stimulus parameters (i.e. stimulus frequency, measurement duration, rate of change of stimulus magnitude) can be set in advance using the software (see Figure 3-7).

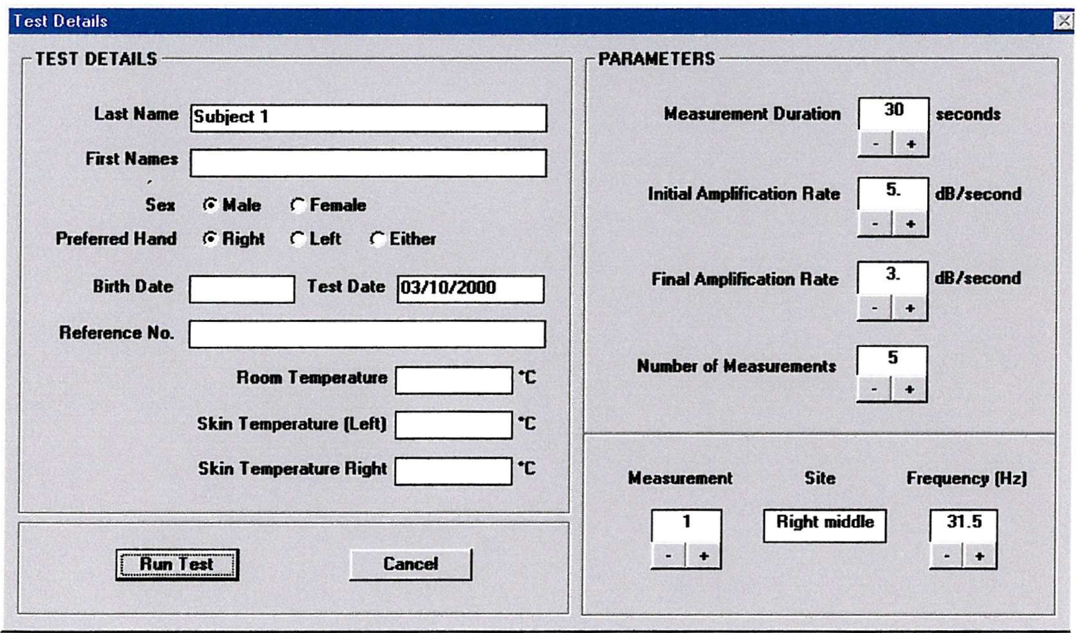


Figure 3-7 View of parameter setting window of the *HVLab* Tactile Vibrometer software.

3.2.3.2 HVLab Data Acquisition and Analysis Software

Vibration stimuli can be created and acquired by *HVLab* Data Acquisition and Analysis Software (version 3.81) via a personal computer. Stimulus parameters (vibration frequency, magnitude, duration) were programmed and controlled using the software.

The computer was fitted with anti-aliasing filters (TechFilter) with an elliptic characteristic; the attenuation rate was 70 dB/octave in the first octave. The signals were then digitised by analogue to digital converter (PCL-818) at a fixed sample rate depending on the stimulus frequency being generated.

3.2.3.3 Thermocouple

Because there are significant changes in vibrotactile sensitivity as the skin temperature changes, particularly at high frequencies (Bolanowski and Verrillo, 1982; Green, 1977), the finger skin temperature of each subject was measured before each session of the experiment. An *HVLab* Thermal Aesthesiometer was used for the temperature measurements. A thermocouple was connected to the control unit. Subjects pinched the thermocouple between two fingers (i.e. thumb and middle finger). Visual feedback was provided by means of digital displays of temperature on the control unit.

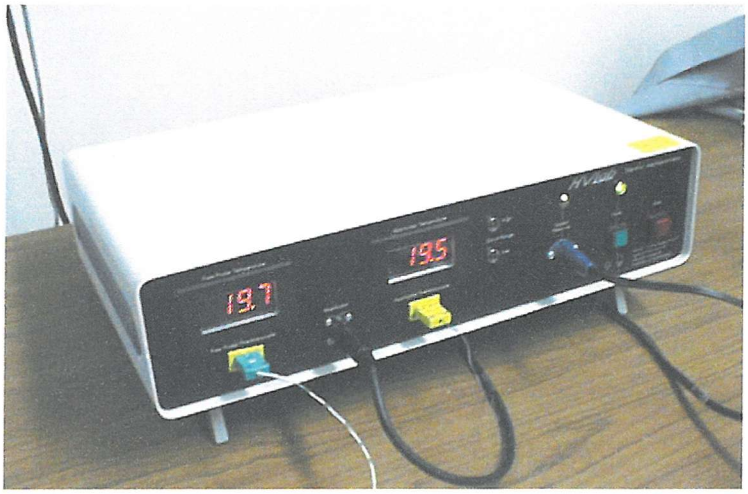


Figure 3-8 Exterior view of the *HVLab* Thermal Aesthesiometer. A thermocouple is placed at the left.

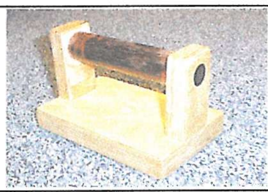
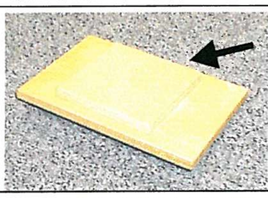
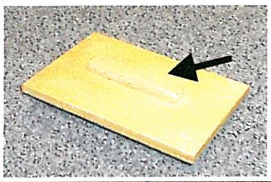
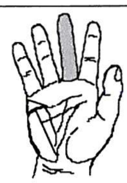
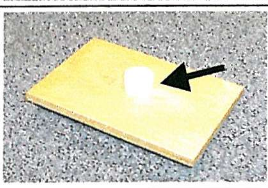
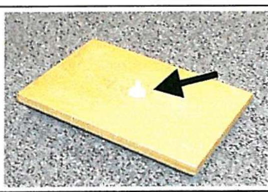
In all studies, the perception measurements were only conducted if the skin temperature was higher than 29° Celsius; the subjects were asked to warm up their hands if the temperature was below the criterion. The room temperature was kept at constant about 23° Celsius.

3.2.3.4 White-noise generator

Some experimental conditions produced audible acoustic noise from the vibrator accompanying the excitation of high frequencies (higher than 100 Hz). For these conditions, subjects were exposed to white noise via a pair of headphones during the tests in order to prevent them from hearing the vibration. Most experiments did not require the masking noise, but subjects wore an earmuff to minimise other environmental noise.

3.3 SKIN-STIMULI CONTACTOR SOURCES

Table 3-3 Details of contactor sources used in the studies * 6 mm diameter circular probe: the same material and size as the Vibrometer probe.

Contactor source	Size of contactor (Material)	Exterior view	Contact location (Nominal)
Handle	30 mm diameter (Wood)		
Flat plate	220 mm by 150 mm (Wood)		
Square probe	120 mm by 120 mm (Wood)		
Square probe	120 mm by 22 mm (Wood)		
Circular probe	30 mm diameter (Nylon)		
* Circular probe	6 mm diameter (Nylon)		

In order to obtain appropriate contact condition between the glabrous skin and the vibrating surface, various skin-stimuli contact sources were designed as shown in Table 3-3. The handle and the flat plate were screwed firmly onto the force transducer. The square probe and the circular probe were attached on the wooden flat plate (220 mm by 150 mm). An armrest was provided for each contactor condition so as to obtain the required arm posture and to maintain the posture constantly during the measurements.

3.4 VIBRATION MEASUREMENT

3.4.1 Direction of vibration

The direction of vibration transmitted to the hand can be defined with two types of biodynamic co-ordinate systems: anatomical or basicentric coordinate systems. Basicentric co-ordinate systems were adopted for these studies and all laboratory studies were performed with vibration in the vertical (x) direction.

3.4.2 Magnitude of vibration

The magnitude of vibration is normally expressed in terms of the acceleration. The unit for quantifying acceleration magnitude is meters per second per second (m/s^2). Root-mean-square (r.m.s.) acceleration is generally adopted as the preferred method of quantifying the magnitude of vibration to which humans are exposured.

The magnitude of vibration may alternatively be defined by the displacement. Some psychophysical response models have been produced in terms of the displacement for the convenience of illustration.

In these studies, the root-mean-square magnitude of the acceleration (ms^{-2} r.m.s) was used to quantifying the perception of hand-transmitted vibration. The acceleration values were then converted to the corresponding displacement, if necessary, to allow comparison with some proposed models.

3.4.3 Calibration of accelerometer

The vibration magnitude was calibrated before each experiment using a Brüel and Kjær Calibration Exciter (type 4294) or a Rion Calibration Exciter (type VE-10), which produce a r.m.s. acceleration of 10.0 ms^{-2} r.m.s. with a frequency of 159.2 Hz.

3.4.4 Background vibration

Background vibration is defined as unwanted vibration noise caused by the measurement apparatus, excluding physiological noise. Physiological noise is produced when a subject contacts the stimulating probe in the absence of the stimulus. This naturally occurs from physiological functions such as blood flow, heartbeat, muscle tremor and respiration.

This background vibration was mainly caused by a vibrator unit (i.e. Tactile Vibrometer, VP 4 and VP 30), dominantly producing electric noise at 50 Hz. The power spectral of the noise from a Vibrometer is shown in Figure 3-8. Reduction of the noise was achieved by connecting a load-dissipating resister to the power amplifier of the vibrator. Measurement noise was reduced by decreasing the range of the acquired acceleration in the computer so as to increase the sensitivity.

The magnitude of background vibration was reduced below the perception threshold of the hand and the finger so that subjects did not feel the background vibration, which might affect their detection of stimuli. The vibration noise was below 0.01 ms^{-2} r.m.s. for the electrodynamic vibrators (i.e. VP 4 and VP 30) and below 0.02 ms^{-2} r.m.s. for the Tactile Vibrometer.

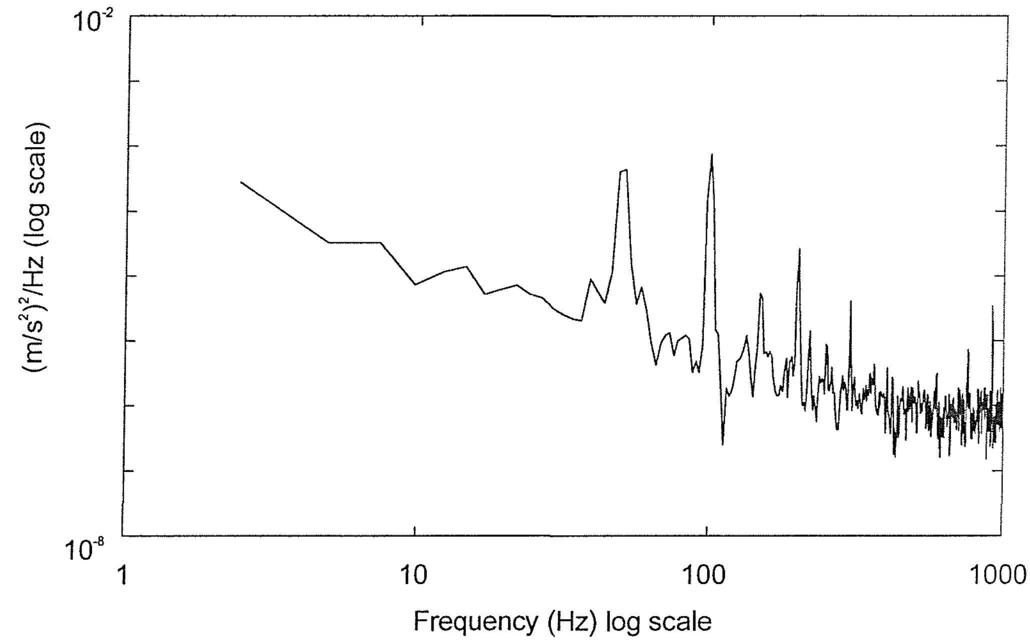


Figure 3-9 Power spectral density of background vibration measured from the Vibrometer (frequency resolution = 2.44 Hz).

CHAPTER 4

STUDY I ABSOLUTE THRESHOLDS: DEPENDENCE ON PSYCHOPHYSICAL MEASUREMENT METHOD

4.1 INTRODUCTION

Absolute thresholds for vibrotactile stimuli have been measured for two purposes: (i) the identification of mechanisms responsible for the perception of vibration or (ii) the detection of disorders caused by hand-transmitted vibration. For diagnostic applications, standardized methods for measuring vibrotactile perception thresholds are required to elicit responses from specific mechanoreceptors and obtain comparable results. As many factors can affect vibrotactile thresholds, well-specified methods for measuring perception thresholds are needed and the effects of different methods must be taken into account when interpreting results.

Among psychophysical measurement algorithms, the adaptive procedure is one in which the stimulus level in one trial is determined by the preceding stimuli and responses, and perhaps it is the most widely used technique for determining sensory thresholds. A draft of International Standard (ISO/FDIS 13091-1, 2001) defines two psychophysical algorithms for determining vibrotactile perception thresholds at the fingertip: (i) the staircase algorithm, in which a sequence of short duration stimuli, with successively increasing (or decreasing) intensities, is applied to the skin until the stimuli are perceived (or no longer perceived), and (ii) the von Békésy algorithm, in which a continuous stimulus, with changing intensity, is used to determine, sequentially, ascending and descending thresholds. The main difference between the staircase algorithm and the von Békésy algorithm is the stimulation procedure and whether the stimuli are presented intermittently or continuously. According to ISO/FDIS 13091-1 (2001), it is preferred to apply intermittent stimulation so as to reduce threshold shifts caused by the vibration stimuli.

With intermittent stimulation, two procedures can be applied to obtain responses from subjects: (i) the 'yes-no' response procedure, in which subjects are presented with a single stimulus and asked to respond whether or not it is perceptible, and (ii) the 'forced-choice' response procedure, in which subjects are presented with a stimulus during one of the periods and then asked to choose which observation period contained the stimulus. The 'yes-no procedure', in which a stimulus is always present on every trial, may have the disadvantage that the subjects are free to set their own criterion for making the "yes" response. Many psychophysical experiments choose forced-choice procedures, in which the signal detection criterion can be brought under the control of the experimenter. The forced-choice staircase procedure is most frequently used with just two alternatives (i.e. the two-interval forced-choice, 2IFC, procedure; Rose *et al.*, 1970).

Although a few studies have discussed the use of different psychophysical methods (e.g. Maeda, 1992; Maeda and Griffin, 1995), there appears to be no study investigating how the two different types of stimulation (i.e. intermittent or continuous) or the two different response procedures (i.e. 'yes-no' or 'forced-choice') influence measures of vibrotactile thresholds.

This study was conducted to compare vibrotactile thresholds at the fingertip between three methods, using two different psychophysical algorithms (the staircase and the von Békésy algorithms). The difference in thresholds between intermittent and continuous stimulation, and between 'yes-no' and 'forced-choice' (2IFC) response procedures were compared. If perception thresholds are influenced by the use of different psychophysical algorithms, this must be taken into a consideration in the experimental design of the current research in order to obtain consistent results between the studies.

4.2 METHOD

Three psychophysical measurement methods, Methods A, B and C, were defined in the study. These employed the possible combinations of continuous and intermittent stimulations with 'yes-no' and 'forced-choice' responses. The combination of continuous stimulation with 'forced-choice' responses is not possible.

Method A: von Békésy algorithm (continuous stimulation)

Method B: Staircase algorithm (intermittent stimulation) 'yes-no' procedure

Method C: Staircase algorithm (intermittent stimulation) 'forced-choice' procedure

4.2.1 Subjects

Twelve males participated in the study, aged 22 to 27 years (mean 24.4 years, standard deviation, SD 2.19 years) with an average stature of 180.7 cm and an average weight of 74.7 kg. Subject information (i.e. body characteristics, health conditions, medical histories and vibration exposures) was collected using a questionnaire (see Appendix A). All subjects were non-smokers, right handed, and free from vibration injuries or history of occupational exposure to hand-transmitted vibration and relevant illness.

4.2.2 Apparatus

Vibrotactile thresholds were determined using the *HVLab* Tactile Vibrometer (see Table 3-2 for the skin-stimulator contact conditions, also see Figure 3-3 for the schematic view), employing different arrangements of equipment (see Figure 3-1 for an illustration). Arrangement B was used for Method A and arrangement C for Methods B and C.

4.2.3 Experimental procedure

Subjects attended one session lasting up to 45 minutes. They were asked not to consume coffee, tea or alcohol for at least two hours prior to the session. Finger skin temperature was measured before and after the tests using an *HVLab* Tactile Aesthesiometer. Tests only proceeded if the skin temperature was above 29° Celsius. The room temperature was kept at about 23° Celsius. Subjects were provided with written instructions prior to participating in the experiment (see Appendix B-1).

A view of the threshold measurement apparatus with a subject is shown in Figure 4-1. Sinusoidal vibration stimuli were delivered to the distal phalanx of the middle finger. Four tests were performed for each condition so as to determine vibrotactile thresholds at the four preferred octave centre frequencies from 16 to 125 Hz. The order of presenting the three conditions was balanced and the order of presenting the four frequencies was randomised.

Figure 4-1 Experimental view of vibrotactile threshold measurement using a *HVLab* Tactile Vibrometer.

4.2.4 Threshold measurement algorithms

Method A: von Békésy algorithm (continuous stimulation)

The magnitude of vibration increased or decreased continuously at a constant rate (test magnitude increment = 3 dB/s, initial magnitude increment = 5 dB/s). The direction of change of stimulus magnitude was reversed according to the response of the subject; the magnitude decreased until the subject no longer perceived vibration and then increased until the subject began to perceive the vibration. The subject responded by pressing a button when perceiving vibration. A test was terminated after 30 seconds. Thresholds were calculated as the arithmetic mean of the mean peak and the mean trough (expressed in ms^{-2} r.m.s.), ignoring the first cycle of the measurement. A schematic time history of the r.m.s. values of the vibration stimuli during an example test is shown in Figure 4-2.

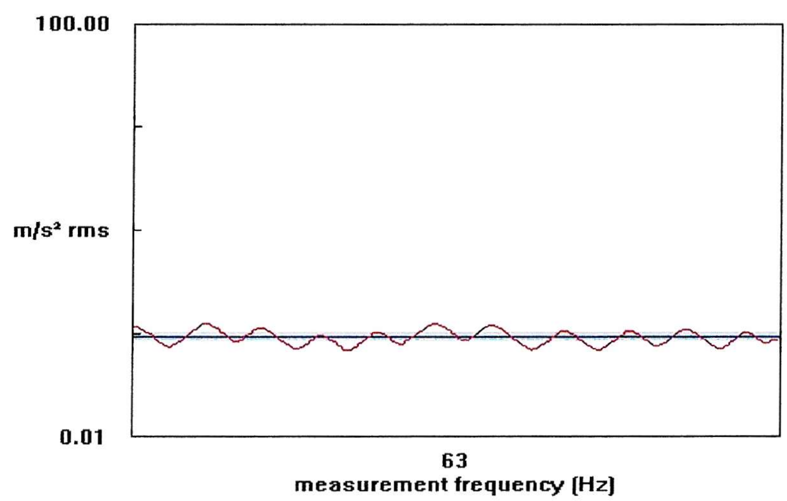


Figure 4-2 Threshold recording by the Békésy method. (Test frequency = 63 Hz, test duration = 30 seconds).

Methods B and C: Staircase algorithm (intermittent stimulation)

The three-down one-up rule was used for both Method B and Method C in conjunction with the staircase (i.e. up-and-down) algorithm. A typical set of data for a threshold measurement is shown in Figure 4-3. The vibration stimulus intermittently increased in intensity by 2 dB (25.8% increment) after a negative (incorrect) response from a subject and decreased by 2 dB after three consecutive positive (correct) responses. The step rate at 2 dB in magnitude was chosen as it is known that the ....

The measurement was terminated after six reversals: a point where the stimulus level reversed direction at either a peak (marked as *p* in Figure 4-3) or a trough (marked as *t* in Figure 4-3). 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):

$$\text{Absolute threshold} = \frac{\left(\sum_{i=2}^{i=3} p_i + \sum_{j=2}^{j=3} t_j \right)}{N}$$

where p_i is the vibration magnitude of peak *i*, and t_j is the vibration magnitude of trough *j*; *N* is the number of reversals.

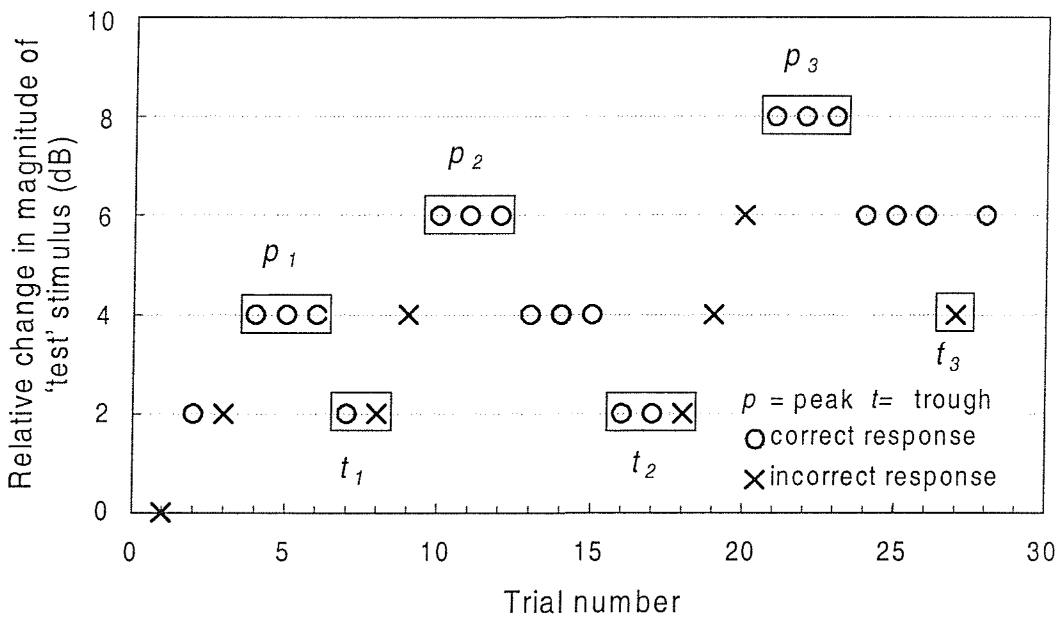


Figure 4-3 Typical data obtained by the staircase algorithm (employed for Method B and Method C). The three-down one-up rule was used. The thresholds were determined from the mean of the peaks and troughs omitting the first peak and first trough.

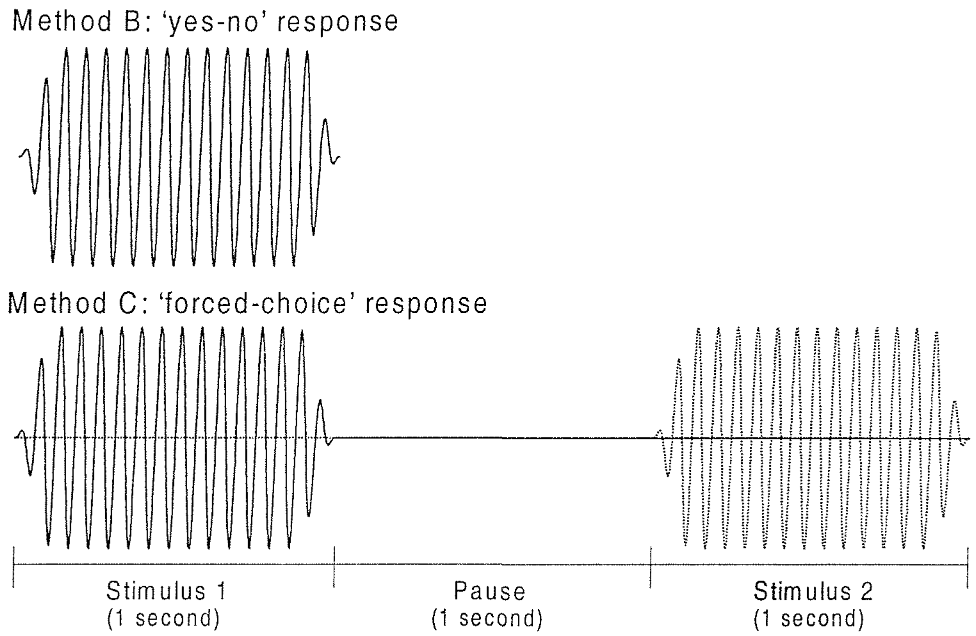


Figure 4-4 Schematic presentation of stimulus design used for Method B ('yes-no' response) and Method C ('forced-choice' response).

Absolute vibrotactile thresholds are normally estimated from the acceleration level corresponding to 50% probability of detecting the vibration stimulus. However, when using forced-choice, it is required to determine more than 50% of positive responses, as 50% of correct responses can be obtained by guessing, such as when subjects do not detect the stimulus. Zwislocki *et al.* (1958) introduced an efficient method of estimating thresholds for other than 50% of positive responses by modifying the rule for presenting stimulus intensities from the simple staircase method. A 'three-down one-up' rule gives thresholds corresponding to 79.4% correct responses: close to half-way between a chance response (i.e. 50 %) and certainty (i.e. 100 %).

Two different response procedures were used to obtain thresholds with the staircase algorithm. With Method B, single vibration stimuli were presented, each 1-second in duration. The subjects' task was to indicate whether they perceived the vibration stimulus or not: a 'yes-no' response. They responded saying, "yes" or "no". With Method C, subjects were presented with pairs of stimuli, each 1-second in duration, separated by a 1-second pause. The two observation periods were designated to the subjects by lights. The subjects' task was to judge whether the first or the second stimulus contained vibration: a 'forced-choice' response. They responded saying, "first" or "second". Figure 4-4 shows a schematic view of the stimuli used in Method B and Method C.

The measurement conditions employed for the three psychophysical methods used in the study are summarised in Table 4-1. For each method, vibrotactile thresholds were determined at the four preferred octave centre frequencies from 16 to 125 Hz. The order of presenting the three methods was balanced and the order of presenting the four frequencies was randomised.

Table 4-1 Summary of the three psychophysical methods.

	Method A	Method B	Method C
Algorithm	Von Békésy	Staircase (3-down 1-up rule)	Staircase (3-down 1-up rule)
Stimulation	Continuous	Intermittent	Intermittent
Response procedure	Yes-no	Yes-no	Two-interval forced-choice (2IFC)
Intermittent stimulation	-		
-burst duration		1.0 s	1.0 s
-quiescent duration		> 1.0 s	1.0 s
Continuous stimulation		-	-
-maximum duration	30 seconds per test		
Step rate	3 dB/s	2 dB	2 dB
Trial number	-	20-25 trials	25-30 trials
Subject response	Stop button (press-yes, release-no)	Oral (yes or no)	Oral (1st or 2nd)
Calculation of thresholds	Mean of reversals (> 6 reversals)	Mean of last 4 reversals	Mean of last 4 reversals

4.3 RESULTS

Figure 4-5 shows individual vibrotactile thresholds of twelve subjects measured by the three psychophysical algorithms. Although threshold values varied between subjects, a trend can be seen: the highest threshold contours tended to be obtained with Method A, whereas the lowest threshold contours tended to be obtained with Method C.

Median vibrotactile thresholds obtained with the three psychophysical methods are shown in Figure 4-6. The thresholds are re-plotted in Figure 4-7 to show threshold shifts in dB between the three psychophysical methods. Median vibrotactile thresholds varied between the three psychophysical methods, with a 3 to 6 dB difference over the frequency range. Lowest thresholds were obtained with Method C (staircase, forced-choice): significant differences in threshold compared to the Method A (Wilcoxon, $p<0.05$, except at 31.5 Hz $p=0.12$) and to the Method B (Wilcoxon, $p<0.05$, except at 16 Hz, $p=0.21$).

There were no significant differences in threshold between Methods A and B (Wilcoxon, $p>0.05$, except at 125 Hz, $p=0.008$).

The frequency dependence of the difference in threshold between the two different methods has been tested. The use of intermittent stimulation (Methods B and C) produced a constant difference in threshold at all frequencies (Wilcoxon, $p>0.05$), whereas the threshold difference measured with continuous stimulation (Method A versus B, Method A versus C) depended on stimulus frequency. A summary of statistical results is shown in Table 4-3.

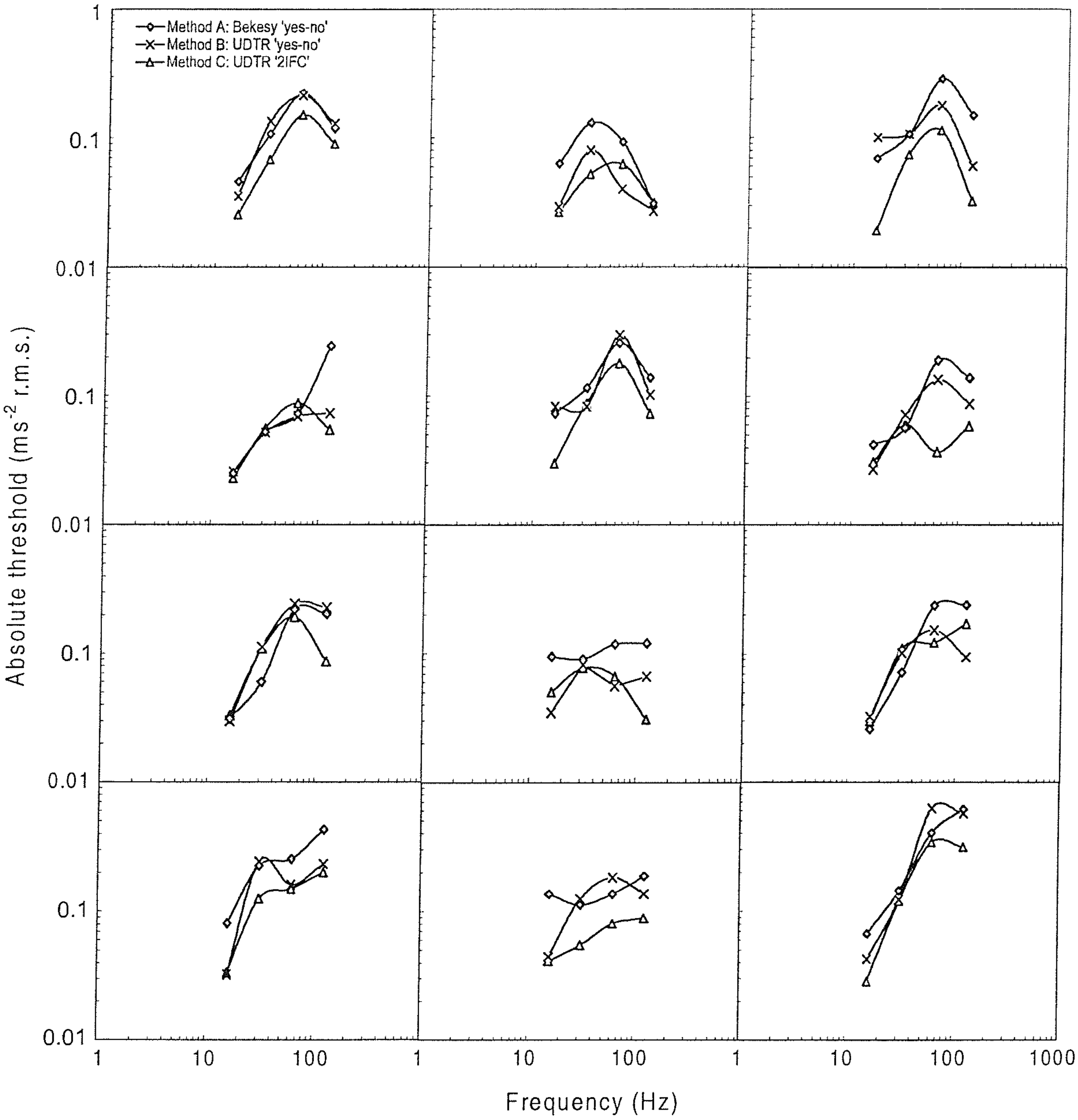


Figure 4-5 Individual threshold data of twelve subjects obtained by three algorithms

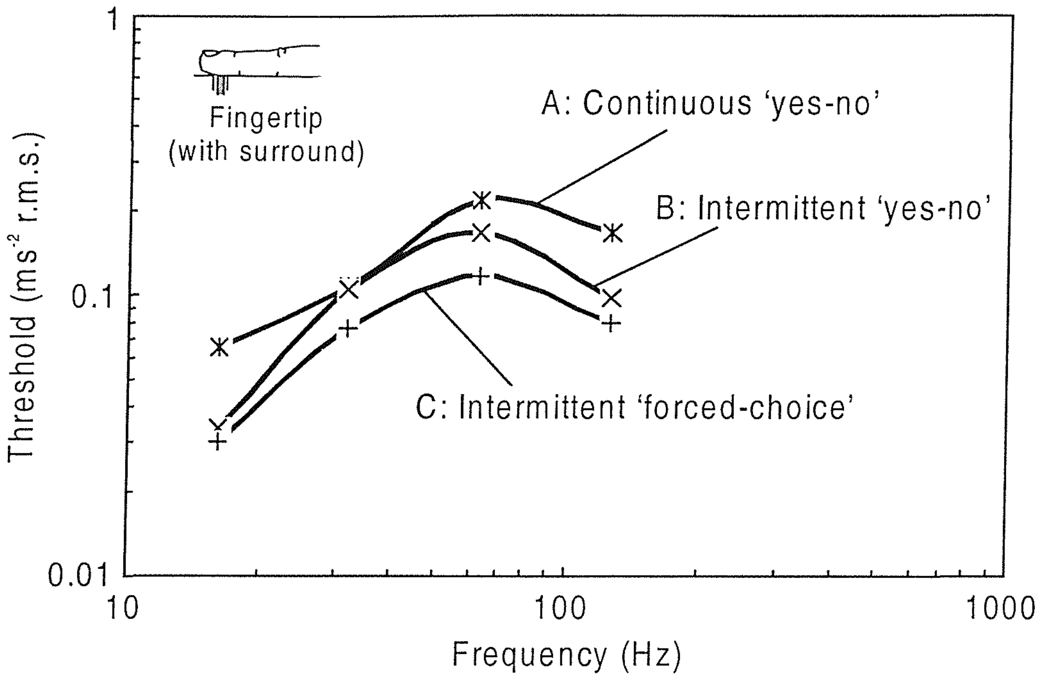


Figure 4-6 Median vibrotactile thresholds for 12 subjects obtained by three psychophysical methods

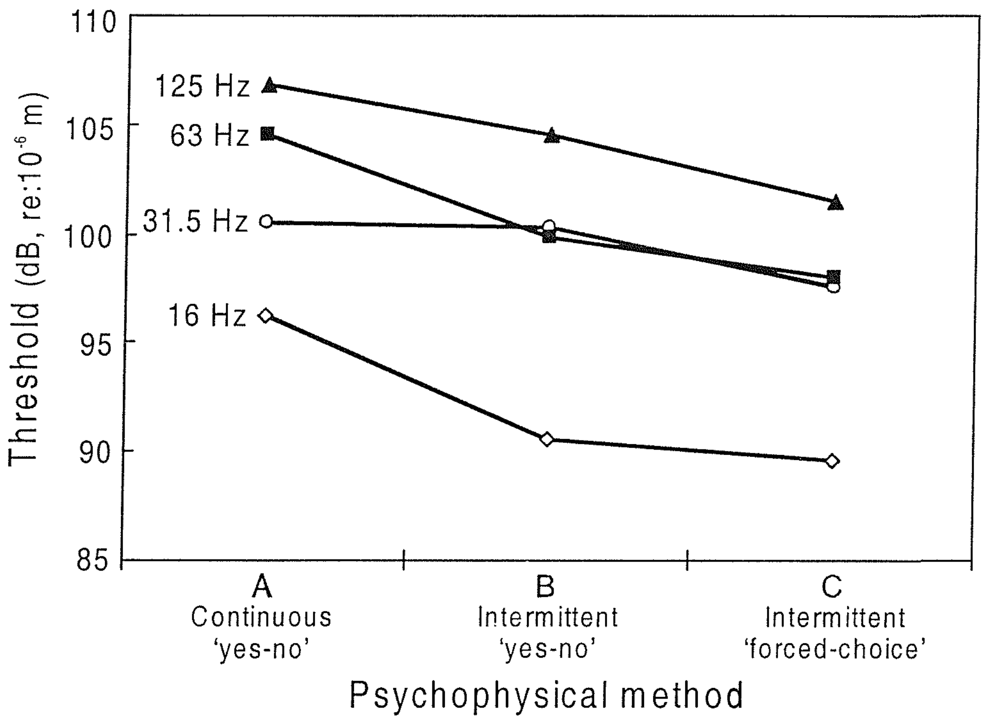


Figure 4-7 Dependence of median thresholds on the three different psychophysical methods.

Thresholds obtained by two different psychophysical methods were generally correlated with each other (see Figure 4-8). Spearman's correlation coefficient was significant at high frequencies (i.e. 125 Hz, 63 Hz) for all combinations of methods ($p<0.05$) also at low frequency (i.e. 16 Hz) between Method A and Method B ($p=0.015$). Within the group of 12 subjects, a person who had higher (or lower) thresholds relative to other subjects when measured by one psychophysical method tended to have higher (or lower) thresholds when measured by another psychophysical method. Lower correlations were obtained at low frequencies (i.e. 16 Hz and 31.5 Hz), partly because thresholds were distributed within a narrow range within the 12 normal subjects. The variability between subjects (expressed as the ratio of the inter-quartile range to the median threshold) was least at low frequencies and greatest at high frequencies for all methods (see Table 4-2).

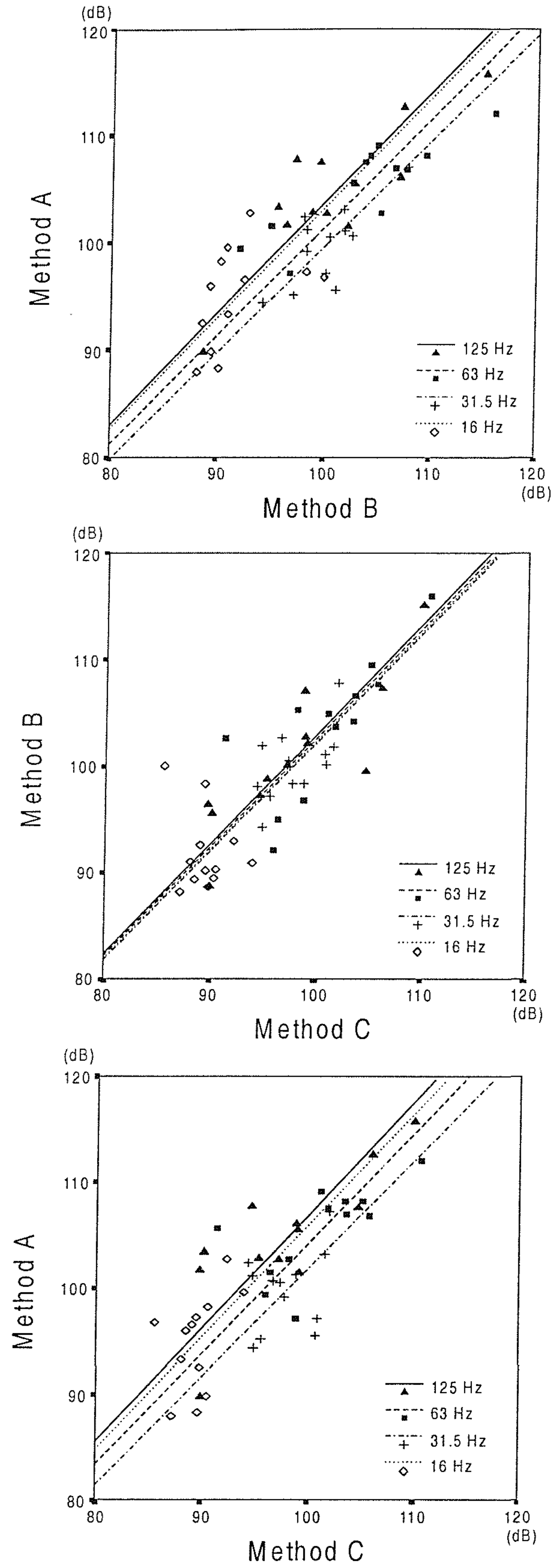


Figure 4-8 Correlation between vibrotactile thresholds for 12 subjects between pairs of psychophysical methods.

Table 4-2 Summary of thresholds of 12 subjects determined by three psychophysical methods (median, inter-quartile-range = IQR, and the ratio of the IQR and the median value)

		Method A	Method B	Method C
16 Hz	Median	0.065	0.034	0.030
	IQR	0.045	0.015	0.008
	IQR/Median	**0.692**	**0.441**	**0.267**
31.5 Hz	Median	0.107	0.104	0.076
	IQR	0.064	0.045	0.054
	IQR/Median	**0.598**	**0.433**	**0.711**
63 Hz	Median	0.221	0.169	0.118
	IQR	0.133	0.151	0.102
	IQR/Median	**0.602**	**0.893**	**0.864**
125 Hz	Median	0.168	0.098	0.080
	IQR	0.119	0.136	0.086
	IQR/Median	**0.708**	**1.388**	**1.075**

Table 4-3 Effect of psychophysical method on vibrotactile thresholds (Wilcoxon matched-pair test).

	16 Hz	31.5 Hz	63 Hz	125 Hz
Methods A and B	-	-	-	**
Methods A and C	**	-	*	**
Methods B and C	-	*	*	*

- No difference (p > 0.05) * p < 0.05 ** p < 0.01

Table 4-4 Correlation coefficient (Spearman) between two methods.

	16 Hz	31.5 Hz	63 Hz	125 Hz
Methods A and B	-	-	**	**
Methods A and C	-	-	**	*
Methods B and C	*	-	**	*

- = no correlation * = significant at 0.05 level ** = significant at 0.01 level

4.4 DISCUSSION

4.4.1 Continuous versus intermittent stimulation (Methods A versus B)

The intermittent stimulation (Method B) tended to lower the absolute thresholds compared to continuous stimulation (Method A) by about 3.2 dB (29% reduction), although the effect of stimulus intermittency was statistically significant only at 125 Hz.

A similar study, Booth (1996) determined vibrotactile thresholds with four different contact locations (fingertip, thenar eminence, inner-side and outer-side of the wrist). The threshold data from the fingertip were compared with the present data from Method A as the measurement conditions (i.e. equipment, algorithm, contact location) were almost the same. As shown in Figure 4-9, the threshold contour obtained from present study was slightly lower than, although very similar to, that presented by Booth (1996).

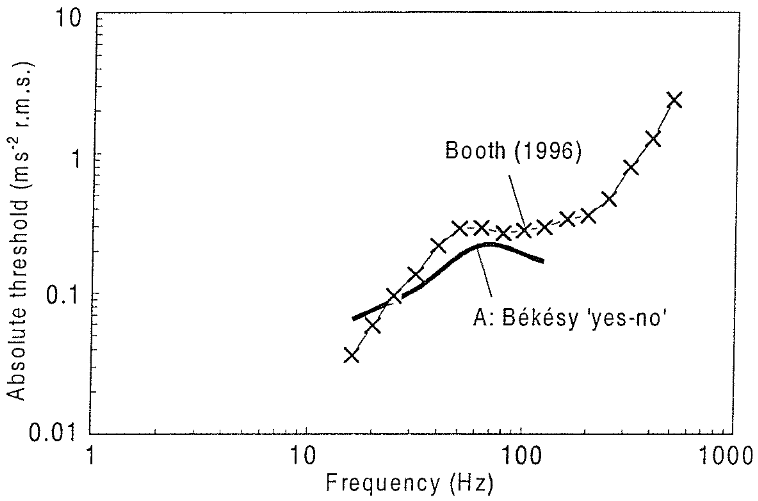


Figure 4-9 Median thresholds of Method A, comparing with the other study (Booth, 1996) used the same algorithm (Békésy, yes-no) and the same equipment.

A choice of different detection probabilities could influence measured thresholds; a higher detection probability in thresholds means a higher percentage of correct response, which results in high value thresholds. However, the present results showed the opposite tendency: Method B gave lower thresholds than Method A, even though Method B provided a threshold for 79.4% probability whereas Method A estimated thresholds for 50% probability (both over the range 0 to 100%). Maeda (1992) compared thresholds at 125 Hz determined by the most orthodox up-down algorithm (using intermittent stimulation) and the von Békésy algorithm (using continuous stimulation), both estimating a 50% threshold, and found higher thresholds with the von Békésy method.

Maeda and Griffin (1995) measured 125 Hz vibrotactile thresholds using the staircase algorithm with seven different rules allowing the estimation of 50% thresholds. The results were compared with those obtained in a previous study using the von Békésy algorithm (the same as Method A) and they again found higher thresholds with continuous stimulation than with intermittent stimulation.

Stimuli at 125 Hz in the present study were likely to be mediated by FA II (Pacinian corpuscles). It is known that the Pacinian system is capable of 'temporal summation' in which thresholds decrease as the stimulus duration increases, up to about 0.6 seconds (Gescheider *et al.*, 1978). Therefore, when vibration magnitude increases during the integration period, the intensity at the moment of perception via the Pacinian system may need to be higher than when the stimulus is of constant magnitude. When vibration magnitude decreases during the integration period, the magnitude at the moment of loosing perception via the Pacinian system may be lower than when the stimulus is of constant magnitude. However, if there is exponential integration over the previous 0.6 seconds, the bias introduced by increasing magnitude may differ from that introduced by decreasing magnitude. This implies that the higher the rate of change of stimulus magnitude the greater the change in thresholds. Löfvenberg and Johansson (1984) and Lundström (1984a) employed 7.5 and 10.0 dB/s, respectively for vibrotactile measurements using the von Békésy algorithm. Their results are more than a factor of 3 to 5 greater than the current results using Method A, although the large difference may not be entirely due to the different rate of change of stimulus magnitude.

Thresholds for detecting the vibration stimuli may have been influenced by previous stimulation causing a shift in mechanoreceptor sensitivity (e.g. by masking, or as a result of a temporary threshold shift). If this occurred, continuous stimulation would be expected to raise the threshold more than intermittent stimulation (as in this study). Gescheider *et al.* (1989) investigated stimulus onset asynchrony (SOA) functions using a masker 20 dB above the threshold level. It was found that the greatest elevation of threshold occurred when the test stimulus was presented close to the time of onset or cessation of the masking stimulus, and then gradually disappeared as the interval between the test and the masking stimulus increased up to about 0.6 seconds. Harada and Griffin (1991) measured vibrotactile thresholds at the fingertip after exposure to hand-transmitted vibration at 20 ms^{-2} r.m.s. for five minutes. The results showed that exposure to vibration at higher frequencies (more than 63 Hz) induced significant TTS (temporary threshold shift) for FA II (Pacinian corpuscles), but there was a lower TTS for FA I (Meissner's corpuscles) when exposed to lower frequency vibration (less than 63 Hz). Thresholds shifts have not been reported at vibration levels associated with the measurement of thresholds; however, such an effect would be consistent with higher thresholds obtained when using continuous stimulation and they cannot be ruled out without further study.

The reaction time of subjects when responding to stimuli of increasing or decreasing magnitude may have an effect on reported thresholds, irrespective of any temporal integration, masking or TTS effects. In this study, the stimulus in Method A increased at a rate of 3dB/s, so a 3 to 6 dB shift in thresholds would require a reaction time of 1 to 2 seconds, far greater than reaction times to supra-threshold stimuli. Reaction times tend to be longer with stimuli close to threshold but this might be considered to be a matter of temporal integration rather than reaction time. The task in Method A was somewhat predictable and subjects may be able to anticipate the stimulus, so shortening reaction times. A reaction time effect would tend to raise the average thresholds of a subject with Method A if it applied equally to the pressing and release of the button indicating the detection of a stimulus.

With Method A (von Békésy algorithm) the stimulus was present at all times and so there was not a clear 'contrast' between moments when the stimulus was present and moments when it was absent. With Method B (intermittent stimulation) observers may have noticed the difference in sensation at the start or end of stimulation, even though at all times there may have been a sensation similar to that caused by the vibration. This opportunity to distinguish 'signal' from 'noise' may have made it easer to detect the stimulus with Method B and resulted in lower thresholds with this method.

4.4.2 'Yes-no' versus 'Forced-choice' response procedures (Methods B versus C)

Employing different response procedures also seemed to shift thresholds. The 'forced-choice' procedure (Method C) significantly lowered thresholds by about 2.2 dB (22% reduction) compared with the 'yes-no' procedure (Method B). This was evident from the middle graph of Figure 4-8 that all the regression lines were overlapped, indicating that the thresholds obtained by Method B elevated at constant by about 2.2 dB (22%) relative to the thresholds obtained by Method C with irrespective to the stimulus frequency. There may be a criterion difference between the two response procedures. With the 'yes-no' procedure, subjects can wait for sufficient stimulus intensity to give a correct response: subjects may tend to give negative answers until they detect the stimulus with certainty so as to avoid being wrong. With the 'forced-choice' procedure, subjects were forced to give an answer following each pair of stimuli and could not avoid errors. They may have detected a faint stimulus and given correct responses at a level where they had insufficient confidence to respond with 'yes' when using the 'yes-no' procedure.

4.5 CONCLUSIONS

The psychophysical method had a significant influence on vibrotactile thresholds: intermittent stimulation lowered thresholds compared with continuous stimulation at 125 Hz, and the 'forced-choice' procedure lowered thresholds compared with the 'yes-no' response procedure at all frequencies except for 16 Hz Possible explanations for the findings include: (i) the response characteristics of the mechanoreceptive system (the sensitivity of the Pacinian system changes as a function of stimulus duration), (ii) masking, or TTS, effects whereby stimulus detection is reduced by previous stimulation, (iii) easier detection of 'signal' from 'noise' when a clear contrast between stimulation and no stimulation occurs, and (iv) criterion shifts in detection by observers. It is concluded that the psychophysical method has a sufficiently large effect on thresholds for it to be taken into account when measuring and comparing thresholds.

The results imply that vibrotactile thresholds obtained by different psychophysical measurement methods may not be comparable. It was resolved by present author that a single psychophysical measurement methods should be employed in the present research so as to allow comparisons of thresholds between independent studies. The present research intends to determine a variety of psychophysical quantities including difference thresholds and masked thresholds; a two-alternative forced-choice method seemed an appropriate method as it can provide reference stimuli in single trial. The later studies in the research (exclude Study 5) therefore employed two-alternative forced-choice method.

CHAPTER 5

STUDY 2 ABSOLUTE THRESHOLDS: COMPARISON BETWEEN THE FINGERTIP AND THE WHOLE HAND

5.1 INTRODUCTION

Vibration perception may be produced in various areas of glabrous skin, including the fingers and the palm of the hand. There are many practical situations where vibration enters the hand through contact with the surfaces of vibrating power tools or vibrating objects held in the hand.

A few studies have investigated the perception of vibration in the glabrous skin using vibration transmitted to the whole hand. Miwa (1967) determined absolute thresholds for hand-transmitted vibration over the range 3-300 Hz by means of the whole hand pressing on a flat plate. Reynolds *et al.* (1977) presented absolute threshold contours with a handle grasping posture. Much research has been carried out to determine vibrotactile perception thresholds at the fingertips or the thenar eminence. It was been revealed in the literature review that the threshold contours for the whole hand looked different from those for the fingertip, or other local areas in the hand (e.g. thenar eminence): greater sensitivity at higher frequencies (around 100-200 Hz) when applying vibration to the whole hand. It is reasonable to assume that whole hand contact produced lower thresholds than at the fingertip at high frequency due to spatial summation via the Pacinian system (see review by Gescheider *et al.*, 1976). However, it is known that there are many variables influencing threshold values (e.g. contact conditions, methods, subjects) so perception thresholds determined in different studies may not be comparable, or at least it is not identified which variable caused the sensitivity differences and what sensory mechanisms were involved. No studies have been found comparing thresholds at the fingertip with those on the whole hand.

5.2 OBJECTIVES

The objectives of this study were:

- To determine absolute perception thresholds for vertical sinusoidal vibration over the frequency range 8 to 500 Hz.
- To compare the thresholds at the fingertip and the whole hand.
- To examine the effect of hand posture (grasping a handle and the palm pressing on a flat table).

5.3 EXPERIMENTAL DESIGN

5.3.1 Subjects

Twelve healthy male volunteers participated in the study. They were aged between 22 and 33 years (mean 24.6 years, standard deviation 3.03) with a mean height of 179.5 cm and a mean weight of 73.0 kg. The health questionnaire (see Appendix A) enabled the experimenter to exclude subjects had with any history of exposure to hand-transmitted vibration or any neurological symptoms. All subjects were non-smokers, right handed and had not been exposed to severe hand-transmitted vibration.

5.3.2 Hand and finger dimensions

Dimensions of the right hand and the middle finger were measured using a pair of vernier callipers (accuracy of 0.1 mm) so as to examine any correlation with the threshold data. The length, breadth and depth of the hand and the finger were defined from the method given by Garrett (1970). Wrist circumference was measured by tying a piece of string around the wrist. The hand volume was calculated assuming the form of an elliptical cylinder and determined by:

$$\textit{Hand volume} = \textit{hand length} \times \pi \times (\textit{hand width} \times \textit{hand depth} / 4)$$

A diagram of the measurement locations and a summary of the results are shown in Figure 5-1 and Table 5-1, respectively.

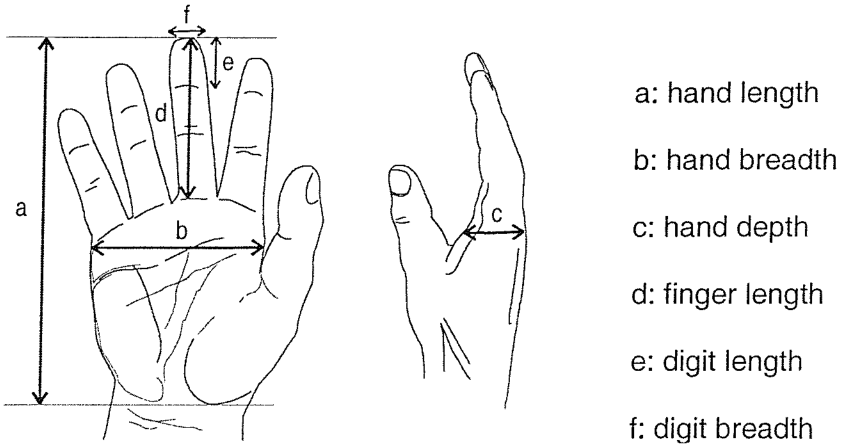


Figure 5-1 Schematic descriptions of measured dimensions of the hand.

Table 5-1 Dimensions of hand and finger for twelve subjects. Mean and standard deviation, SD, are shown (mm).

	a) hand length	b) hand breadth	c) hand depth	d) finger length	e) digit length	f) digit breadth	g) wrist circumference
Mean	191.08	85.92	30.95	80.45	16.65	14.07	171.75
SD	6.39	3.32	2.50	4.52	0.59	1.12	6.14

5.3.3 Experimental conditions

Absolute perception thresholds for vertical sinusoidal vibration were determined at preferred octave centre frequencies from 8 to 500 Hz. A summary table of the experimental conditions used for each contact condition is shown in Table 5-2.

Table 5-2 Summary of experimental conditions used in the study.

	Condition A	*Condition B*	*Condition C*
Contactor source	Wooden plate	Wooden handle	Nylon circular probe
Dimension of contactor	200 mm × 150 mm	30 mm diameter	6 mm diameter probe 10 mm diameter surround
Vibrator	VP 4	VP 4	*HVLab* Tactile Vibrometer
Contact force	10 N	10 N	1 N
Measured frequency	8, 16, 31.5, 63, 125, 250, 500 Hz		
Psychophysical method	Staircase method (2IFC), Three-down one-up procedure		
Masking noise	60 dB(A)		
Skin temperature	> 29 °C		

5.3.3.1 Contact conditions

Thresholds were compared with three contact conditions (Conditions A, B and C). A schematic view of each condition is shown in Figure 5-2.

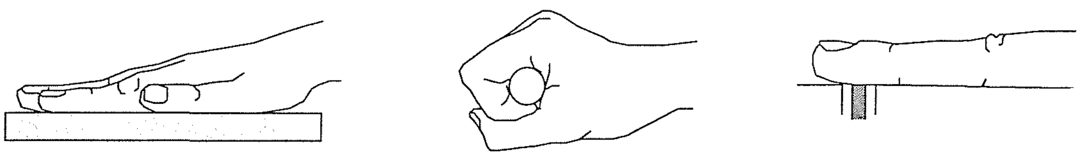


Figure 5-2 Hand/finger positions for the three conditions

<u>*Condition A*</u>

Subjects' right hands were placed on the wooden surface of the flat plate attached to the vibrator (VP 4). They were asked to press the plate with a force of 10 N and maintain the force during the threshold measurements; visual feedback of the force was provided using an analogue meter. The arm was supported by an armrest so as to fix the arm height and the hand position.

Condition B

Subjects gripped the wooden handle with their right hands. They were asked to press the handle downwards with a force of 10 N (with no grip force) and maintain the push force during the threshold measurement. A force meter and an armrest were provided in Condition A.

Condition C

The distal phalanx of the right middle finger was placed over the probe of the Tactile Vibrometer. The finger pushed on the surround with a force of 2 N while the probe applied an upward force of 1 N. Visual feedback of the surround force was shown on an analogue meter. The arm was supported by the vibrometer unit.

5.3.3.2 Psychophysical method

The up-and-down method (staircase algorithm) with a three-down one-up rule using a two-interval two alternative forced-choice (2IFC) tracking procedure was employed for the determination of absolute thresholds. This was the same procedure as Method C defined in the previous study (see Section 4.2). The subjects were asked to detect which of two 3-second time intervals (separated by a 1-second pause) contained the vibration stimulus.

5.3.3.3 Other conditions

There was a little audible noise caused by the VP4 vibrator, mainly at the highest frequency (i.e. 500 Hz). Subjects were presented with a masking noise (60 dB) via a pair of headphones when testing with 500 Hz vibration stimuli for all conditions in order to prevent them from hearing the vibration.

Finger skin temperature was measured before and after the threshold measurements; tests only proceeded if the skin temperature was greater than 29° Celsius. Subjects attended three sessions on three separate days. The order of presenting the three conditions was balanced and the order of presenting the seven stimulus frequencies was randomised.

5.4 RESULTS

Figure 5-3 shows the individual absolute thresholds for each condition. When using the handle and plate (Conditions A and B), similar U-shaped threshold curves were obtained, with most sensitivity at frequencies over the range 100 to 150 Hz. There were no significant differences between the thresholds in the two postures, the whole hand pressing the flat surface or the handle-grasping posture (Wilcoxon, p>0.05).

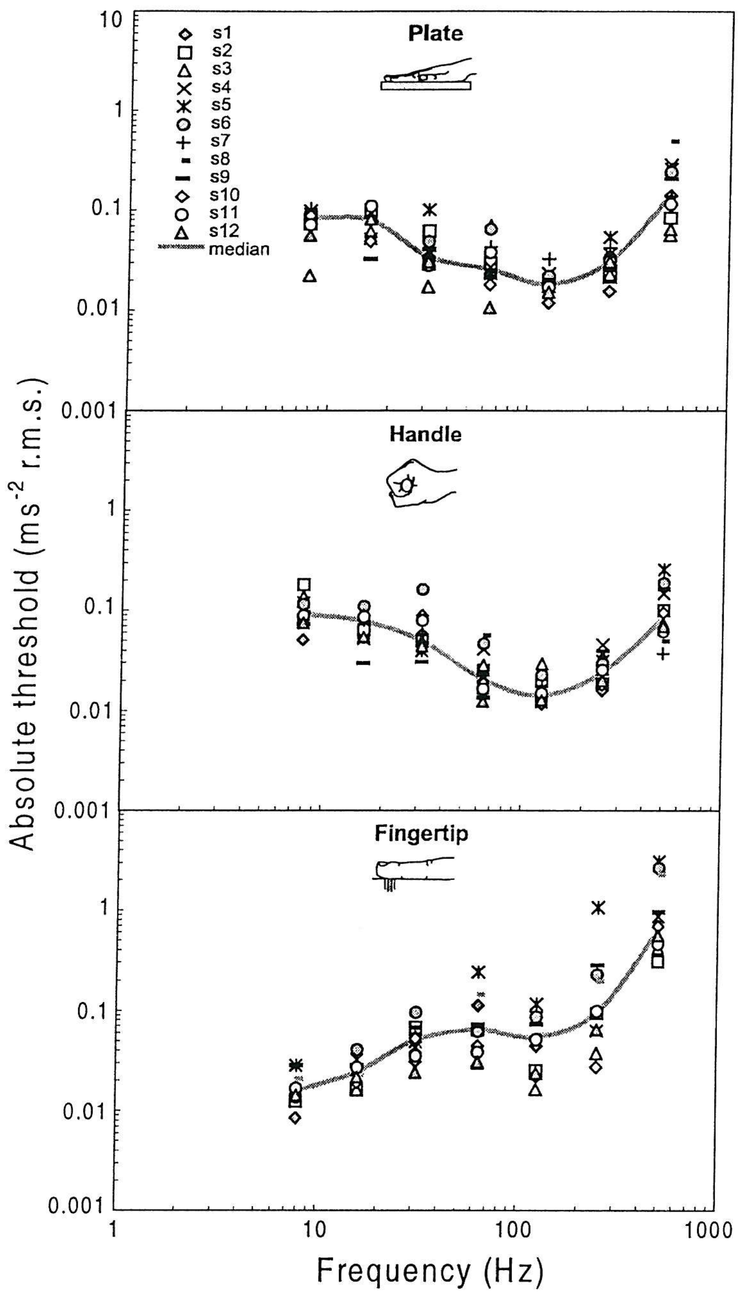


Figure 5-3 Individual thresholds obtained in three conditions. The grey lines show medians of twelve subjects.

Comparing the absolute thresholds between the hand (Conditions A and B) and the finger (Condition C), the absolute threshold curves were significantly different (Friedman, $p<0.005$) except for the frequencies 31.5 and 63 Hz (Friedman, $p>0.05$). Above 63 Hz, the threshold at the fingertip was higher than that of the hand. The differences were approximately 10 dB.

As expected, there were inverse correlations between absolute thresholds and finger skin temperature measured before and after testing (Spearman, $p<0.05$). No significant association was found between VPTs and the age, body size, or hand volume of the subjects.

5.5 DISCUSSION

5.5.1 Comparison of whole-hand versus fingertip (Conditions A and B, versus Condition C)

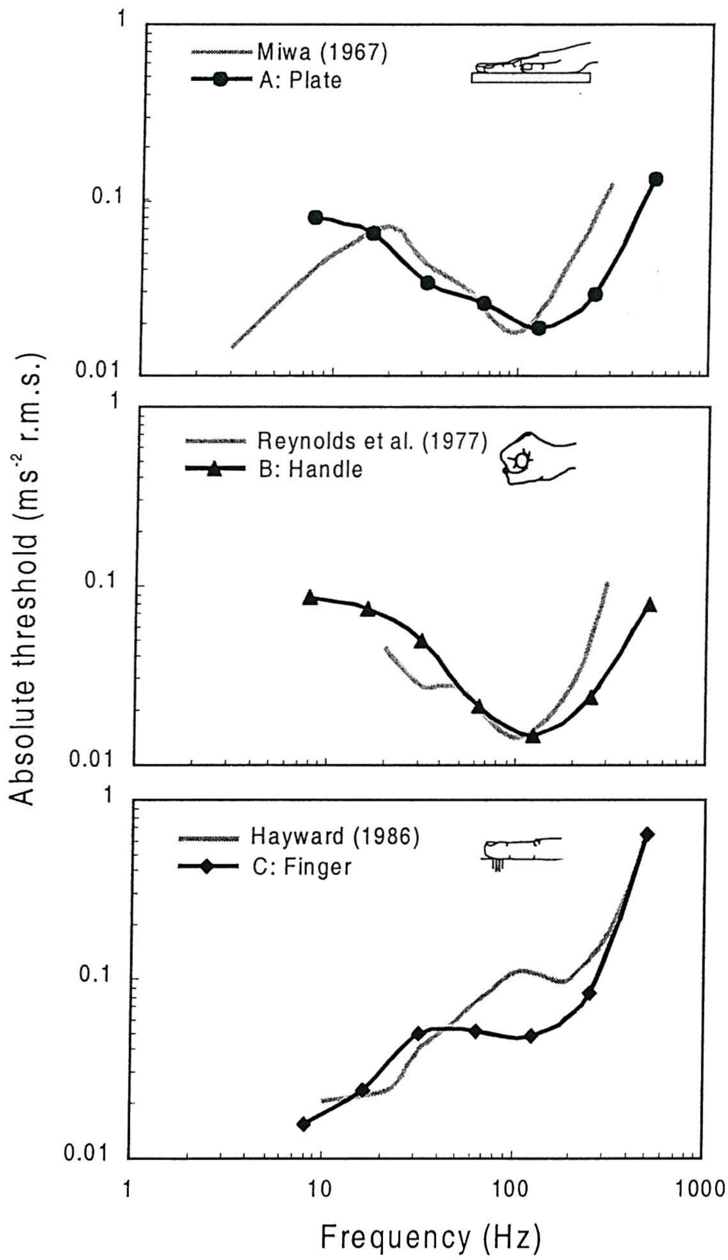


Figure 5-4 Comparisons of absolute perception thresholds obtained from other studies and the current results.

The results indicate large differences in absolute thresholds between whole hand contact (Conditions A or B) and fingertip contact (Condition C). The median thresholds of twelve subjects for the three conditions are shown in Figure 5-5.

The thresholds were compared with results from other studies (i.e., Miwa, 1967 with Condition A; Reynolds *et al.*, 1977 with Condition B; Hayward, 1986 with Condition C) conducted with similar conditions to the present study. It is seen in Figure 5-4 that the threshold contours were fairly similar.

Some of the reasons for the sensory difference in vibration perception between the hand and the finger can be explained in terms of the mechanisms of tactile sensation. There were probably two mechanoreceptor systems involved in the detection of the vibrotactile stimuli in the experiment. The Pacinian system (FA II) was probably mainly responsible for the detection of stimuli at 63 Hz and higher frequencies, while the non-Pacinian system (possibly the FA I) was mainly responsible for detection at frequencies of 31.5 Hz and lower frequencies (Verrillo, 1966b; Gescheider, 1978).

At frequencies above 31.5 Hz, lower median thresholds were obtained with the whole hand in contact with the wooden handle or the wooden plate than with the fingertip in contact with the small circular probe. This is possibly a result of spatial summation among FA II units, as proposed by Verrillo (1966a), adding to perception with the larger contact area of the hand. The contact area of the probe was much smaller than that of the plate or the handle and so the reduction in size may have been responsible for the 10 dB increase in the thresholds at 125 Hz.

At low frequencies below 31.5 Hz, lower thresholds were obtained with the fingertip on the probe than with the wooden plate or the wooden handle. This may have been caused by the surround around the probe increasing the sensitivity of the FA I units. Threshold sensitivity is increased by stimulus gradients when detection occurs via the non-Pacinian system (Verrillo, 1979c; Gescheider *et al.*, 1978).

It was concerned the effect of contact force on thresholds as two different contact forces were applied for the fingertip (1N) and the whole hand (10N); higher pressure was expected with the fingertip compared with the whole hand. As it is known that greater contact force tends to produce lower thresholds (see Craig and Sherrick, 1969), the differences in thresholds seen in present results were not influenced by the applied contact force.

5.5.2 Comparison between two hand postures (Condition A versus Condition B)

The two different hand postures (Conditions A and B: palm pressing on the plate and whole hand grasping the handle) produced similar absolute thresholds with no significant difference. The results can also be explained by the characteristics of the Pacinian and the non-Pacinian systems. Although there was a difference in hand posture, the contact areas between the glabrous skin of the hand and the wooden surface were similar and both had no gradient stimuli over the skin. It might be assumed that in both conditions the thresholds were mediated by the same receptor populations.

The handle-gripping condition provided a slightly more complicated contact condition as the handle would be gripped with different forces (i.e. loose, tight). It is known that the greater the force applied by the hand the higher the transmission of vibration through the hand (Burström, 1994), and this might alter the response of receptor systems.

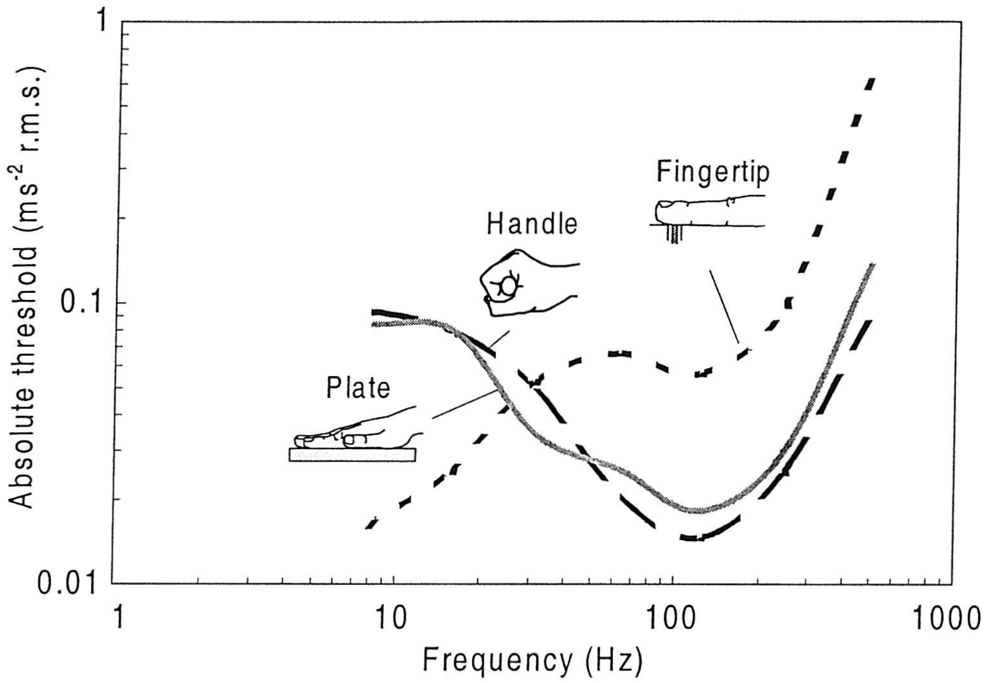


Figure 5-5 Summary results: median absolute thresholds of twelve subjects are shown.

5.6 CONCLUSIONS

There were no significant differences in vibration perception thresholds for two hand postures (flat wooden plate and wooden handle), whereas there were appreciable differences in thresholds between these conditions and vibration of the fingertip. The results appear consistent with the known response characteristics of Pacinian and non-Pacinian systems. The existence of the large sensory difference has not been previously investigated. Thresholds for the perception of hand-transmitted vibration should not be assumed to be the same as thresholds for the perception of finger vibration.

CHAPTER 6

STUDY 3 ABSOLUTE THRESHOLDS: EFFECT OF SURROUND, CONTACT FORCE AND CONTACT AREA

6.1 INTRODUCTION

The previous study (Chapter 5) revealed that there were differences in vibration perception thresholds for the fingertip and for the whole hand over the frequency range 8 to 500 Hz; the results were partially explained by the known responses of Pacinian and non-Pacinian systems: lower absolute thresholds were obtained with the whole-hand at high frequencies (above 63 Hz) due to the response via Pacinian system, whereas higher absolute thresholds were obtained with the whole hand at low frequencies (below 31.5 Hz) due to the response via the non-Pacinian system. However, the results did not fully identify the factors responsible for differing thresholds between the fingertip and the whole hand, since sensitivity at the fingertip was greatly influenced by the use of a surround around the contactor probe. The presence of a surround is expected to restrict vibration propagation via the skin and reduce the Pacinian system response, and also provide a stimulus gradient to enhance the response of the non-Pacinian system (e.g. Gescheider, 1976; Verrillo, 1985; Harada and Griffin, 1991). This was evident from the neurophysiological studies that RA (FA I) and SA I were found to be more sensitive to the edge: stronger response from RA and SA I were obtained when the defined receptive field was placed over the edge of the 6mm diameter contactor rather than covered by the contactor (Johansson *et al*, 1982).

Contact area has been found to be one of the most important parameters affecting tactile sensitivity. Verrillo (1963) originally demonstrated that the threshold sensitivity to a vibrating contactor with a rigid surround (constant gap of 1.0 mm) at the thenar eminence depended, at high frequencies, on the contact area; sensitivity to acceleration increased with increasing frequency up to a maximum at 250 Hz, and sensitivity increased by 3 dB per doubling of contactor area.

Contact force may also influence tactile sensitivity as the pressure on the skin is decreased with increasing the contact area if the contact force remains constant.

Considering the spatial summation effect via the Pacinian system, it was expected that there would be a decrease in thresholds with increasing contact area from the fingertip to the whole hand at frequencies where the response is determined by the Pacinian system.

In this study, absolute perception thresholds for vertical sinusoidal vibration were determined over the frequency range 16 to 125 Hz with varying skin-stimulus contact conditions in order to examine the effects of surround, contact area, contact location and contact force over the glabrous skin of the hand. Some of the contact conditions used in this study were the same as in the previous study so as to make a comparison of results possible, and to test the reproducibility of the perception thresholds in two independent experiments.

6.2 METHOD

6.2.1 Subjects

Twelve healthy males (mean age, 24.3 years) participated in the experiment. All subjects were students or office workers with no history of occupational exposure to hand-transmitted vibration. They were all non-smokers, right handed and free from vibration injuries or history of relevant illness. The hand and finger dimensions of the subjects were measured using a pair of vernier callipers and the results are shown in Table 6-1.

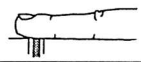
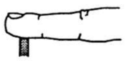
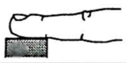
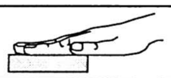
Table 6-1 Body/hand characteristics for twelve subjects

	Height (cm)	Weight (kg)	Hand length (mm)	Hand breadth (mm)	Middle finger length (mm)	Digital phalanx length of the middle finger (mm)	Digital phalanx breadth of the middle finger (mm)
Mean	181.2	75.2	195.8	87.2	81.6	29.6	13.9
Minimum	175.2	70.0	180.0	83.6	76.4	26.0	12.2
Maximum	190.0	85.7	220.0	91.6	88.5	33.0	15.5
SD	4.15	5.14	12.25	3.04	4.39	2.37	1.07

6.2.2 Experimental conditions

Vibration perception thresholds were measured over the glabrous skin of the hand with eight conditions having varying contact area, contact location and contact force. The finger/hand posture and contact force were controlled for each condition and the details are shown in Table 6-2.

Table 6-2 Contact conditions for measuring vibration perception thresholds. *The equipment used for *Conditions A* and *B* was the *HVLab* tactile vibrometer, other conditions were measured with the VP 4 electrodynamic vibrator.

Condition	Finger or hand posture	Contact location	Dimension of contactor	Contact force
A		Distal phalanx of the middle finger	6 mm diameter * (10 diameter surround)	1 N
B		Distal phalanx of the middle finger	6 mm diameter * (no surround)	1 N
C		Distal phalanx of the middle finger	6 mm diameter (no surround)	1 N
D		Distal phalanx of the middle finger	35 mm diameter nylon probe	1 N
E		Distal phalanx of the middle finger	35 mm diameter nylon probe	5 N
F		Whole middle finger	22 × 120 mm wooden plate	5 N
G		Four whole fingers (excluding the thumb)	120 × 120 mm wooden plate	5 N
H		Whole hand	220 × 150 mm wooden plate	5 N

6.2.2.1 Contact conditions

Two devices were employed to deliver vibration stimuli at the finger and hand: the *HVLab* Tactile Vibrometer (for *Conditions A* and *B*) and the Derritron VP 4 electrodynamic vibrator (for *Conditions C, D, E, F, G* and *H*). The set up details and the equipment used in the study are described in Chapter 3 (see Table 3-1 and Figure 3-1).

In order to provide a 'no surround' condition in *Condition B*, a special cover was designed having a circular hole of 60 mm in diameter around the probe and was mounted on the Vibrometer.

Because of the use of two different devices, two conditions (*Conditions B* and *C*) were employed to compare the thresholds determined by the two different devices (but the same contact conditions). It was expected that similar thresholds would be obtained with the two conditions.

A constant contact force was applied (1N for the fingertip and 5 N for the fingers and the whole hand conditions), as it was not possible to control contact pressure, which depends on the size of a subjects' hand. In order to take into account the effect of force, for one of the subjects' the hand and fingerprints were obtained. Figure 6-1 shows the finger and handprints of one subject for the five different contact conditions. The contact areas of other subjects was estimated from the printed area of the one subject by multiplying by the dimension of their hands. The contact pressure for each individual subject was also calculated from these data.

6.2.2.2 Procedure

Subjects attended two sessions on two separate days. The eight conditions were divided into these two sessions (*Conditions A, B, C* and *D* and *Conditions E, F, G* and *H*). Four tests were carried out for each condition, examining the four vibration frequencies (i.e. 16, 31.5, 63 and 125 Hz). The order of presenting the sessions was balanced between twelve subjects. The order of presenting the contact conditions and the test frequencies was randomly arranged.

Prior to each session, the finger skin temperatures of subjects' test hands were measured. The measurements proceeded if the skin temperature was higher than 29° Celsius. The measured temperature was within 29.4 to 35.7° Celsius (mean 32.0° Celsius). The room temperature was kept above 22° Celsius during the sessions.

Subjects placed their middle finger (or their hand, according to the condition being tested) on the contactor probe pressing downwards with the prescribed contact force. Their arm rested on an armrest in order to fix and maintain a constant hand-arm posture.

The contact force was monitored by subjects and the experimenter via a meter. When their contact force became stable, threshold measurements commenced.

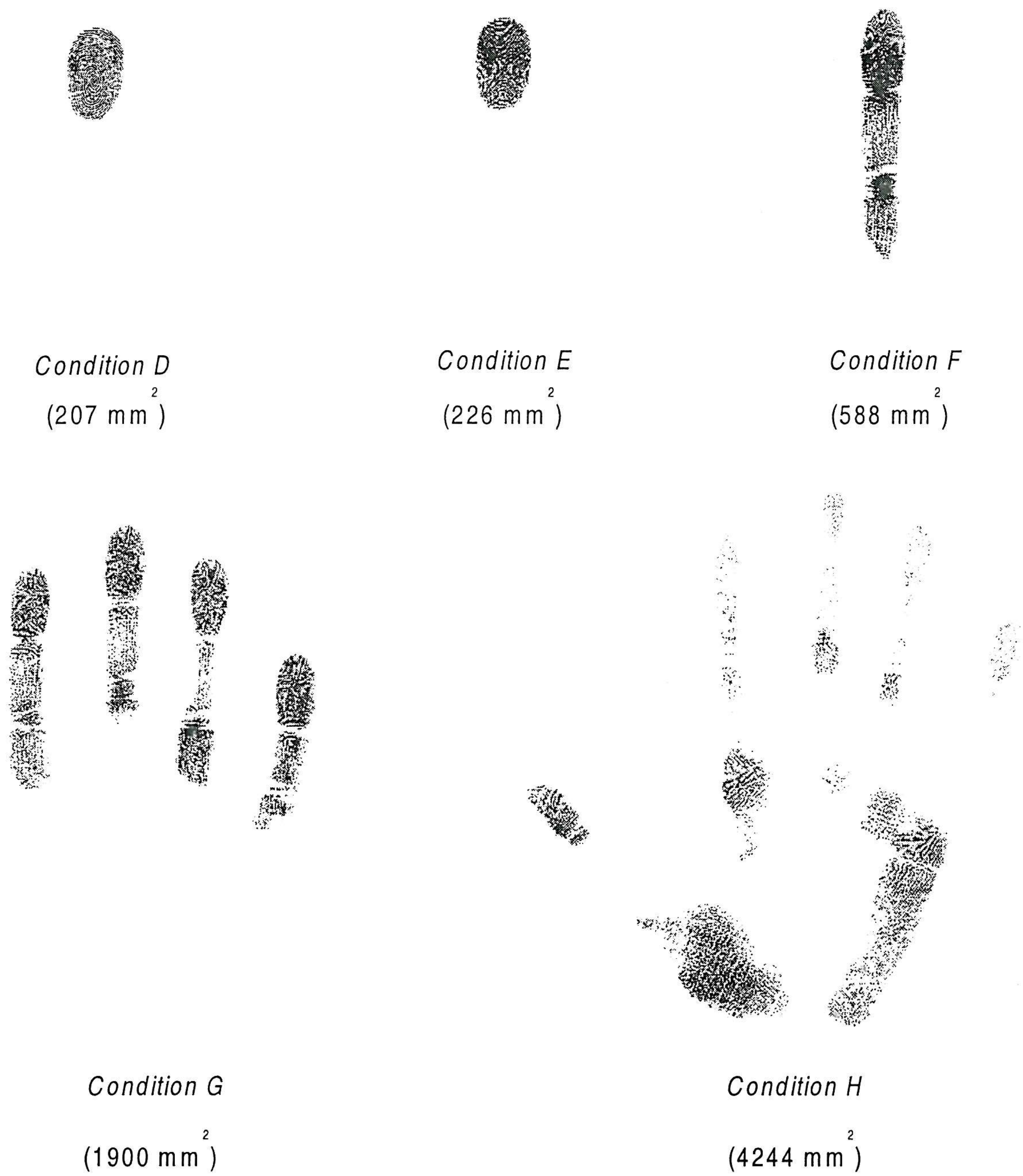


Figure 6-1 Fingerprints and handprints of one subject for *Conditions C, D, E, G* and *H*. The scale of the prints is approximately half of the real scale. The numbers in the brackets are the contact areas calculated from the original prints.

6.2.2.3 Threshold measurement algorithm

The up-and-down transformed response method (UDTR method) with three-down one-up rule was employed for the threshold measurements. The response procedure was the two-interval two-alternative forced-choice (2IFC) tracking procedure. This was the same measurement procedure and the same threshold calculation employed in *Algorithm C* of Study 1 (see Chapter 4).

The task of the subjects was to indicate which of two 1-second intervals (separated by a 1-second pause) contained the vibration stimulus. Threshold measurements were commenced at a stimulus magnitude which the subjects could easily detect, and then the magnitude was decreased and increased according to their responses.

6.3 RESULTS

6.3.1 Effect of surround (*Conditions A* and *B*)

Figure 6-2 shows median thresholds for twelve subjects at the distal phalanx of the middle finger with and without a surround. When the surround was present, the thresholds were significantly decreased by 15.9 dB (a factor of 7) at 16 Hz and significantly increased by 5.6 dB (a factor of 2.3) at 125 Hz.

The effect of the surround was statistically significant ($p < 0.01$, Wilcoxon), except at 63 Hz ($p = 0.814$, Wilcoxon).

The results are consistent with the earlier studies that have examined the effect of a surround (Gescheider *et al.*, 1978; Goble *et al.*, 1996; Harada and Griffin, 1991; Lamoré and Keemink, 1988; Van Doren, 1990), although they applied different contact conditions (e.g. size of contactor, gap distances, contact forces).

6.3.2 Effect of equipment (*Conditions B* and *C*)

As can be seen in Figure 6-2, the median threshold contours of twelve subjects obtained by the two different systems with the same contact condition (*Conditions B* and *C*) were slightly differed in measured thresholds but were not significant in difference ($p>0.1$, Wilcoxon); this implies the vibration perception thresholds were not influenced by the use of the two different vibration devices.

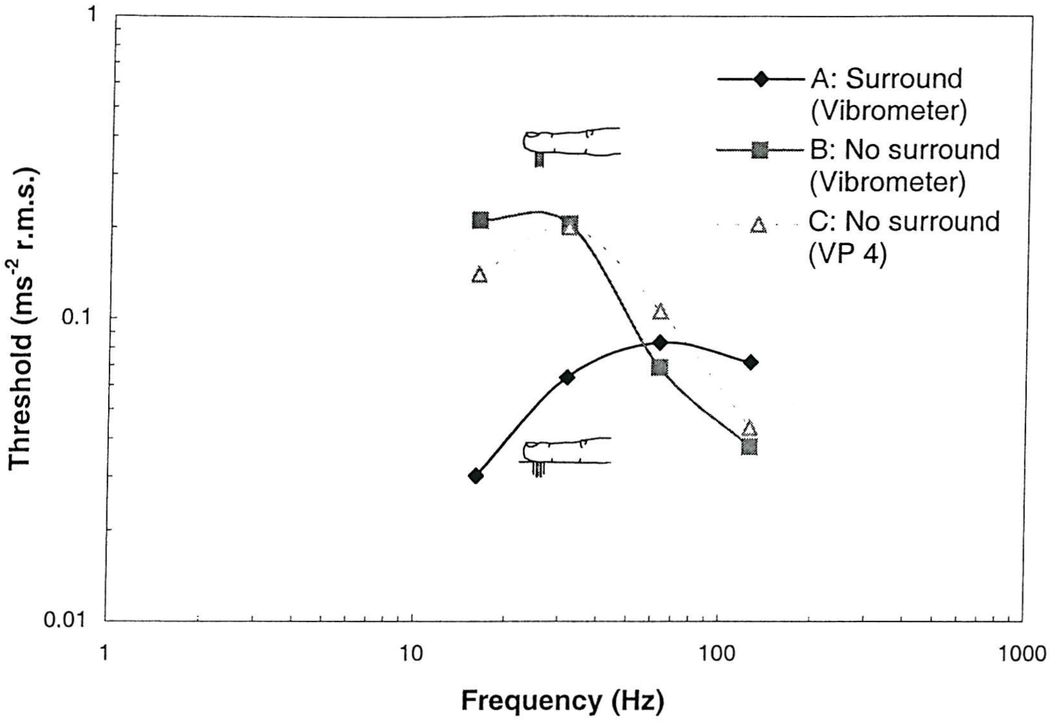


Figure 6-2 Effect of surround on vibration perception thresholds at the fingertip. (Median thresholds for 12 subjects)

Contact probe = 6 mm diameter, 2 mm gap (Conditions B and C), Contact force = 1 N.

6.3.3 Effect of contact force (*Conditions D* and *E*)

Figure 6-3 shows the threshold contours measured with two different contact forces at the fingertip. The greater contact force (Condition E) elevated the thresholds at high frequencies compared with the lesser contact force (Condition D): 3.9 dB threshold increment at 63 Hz and 4.4 dB increment at 125 Hz. Only a small change in threshold was found at low frequencies. The effect of contact force was statistically significant only at 125 Hz (Wilcoxon, $p<0.05$).

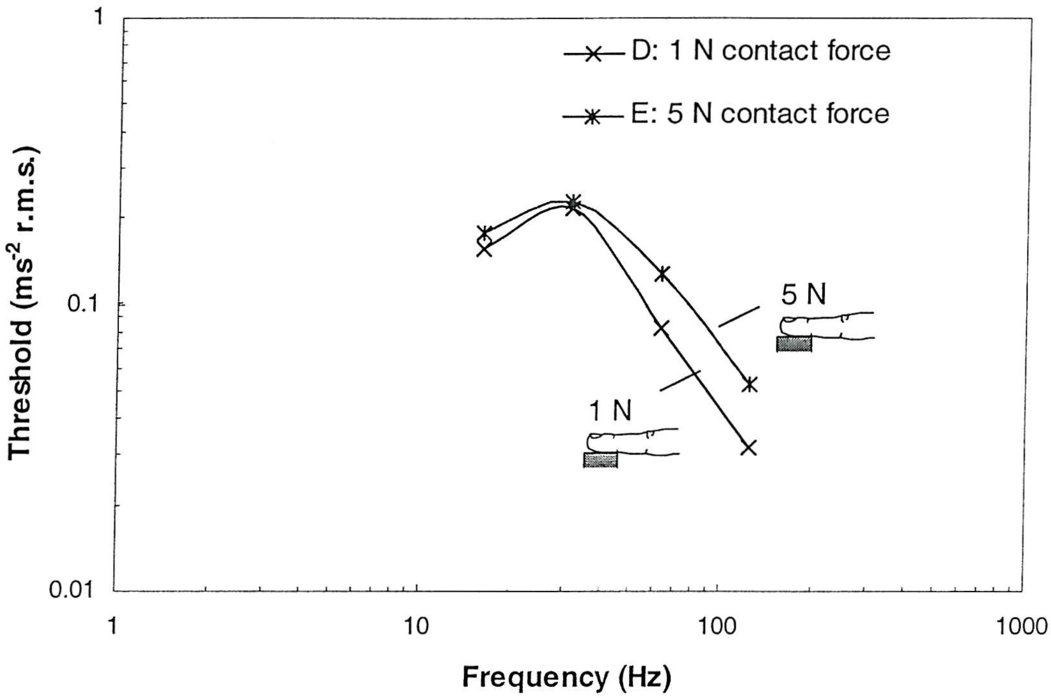


Figure 6-3 Effect of contact force at the distal phalanx of the middle fingertip. (Median thresholds for 12 subjects)

6.3.4 Effect of contact area

6.3.4.1 Within the fingertip

Figure 6-4 shows the median thresholds at the fingertip obtained with two different sizes of contactor (i.e., 6 mm diameter and 35 mm diameter). The median thresholds decreased by about 2.4 dB (about 25% reduction) when using a larger contactor *(Condition D)* compared with the smaller probe (*Condition C*) at the higher frequencies of 63 and 125 Hz. The effect of contact area between *Condition C* and *Condition D* was statistically significant only at 125 Hz (Wilcoxon, $p<0.02$).

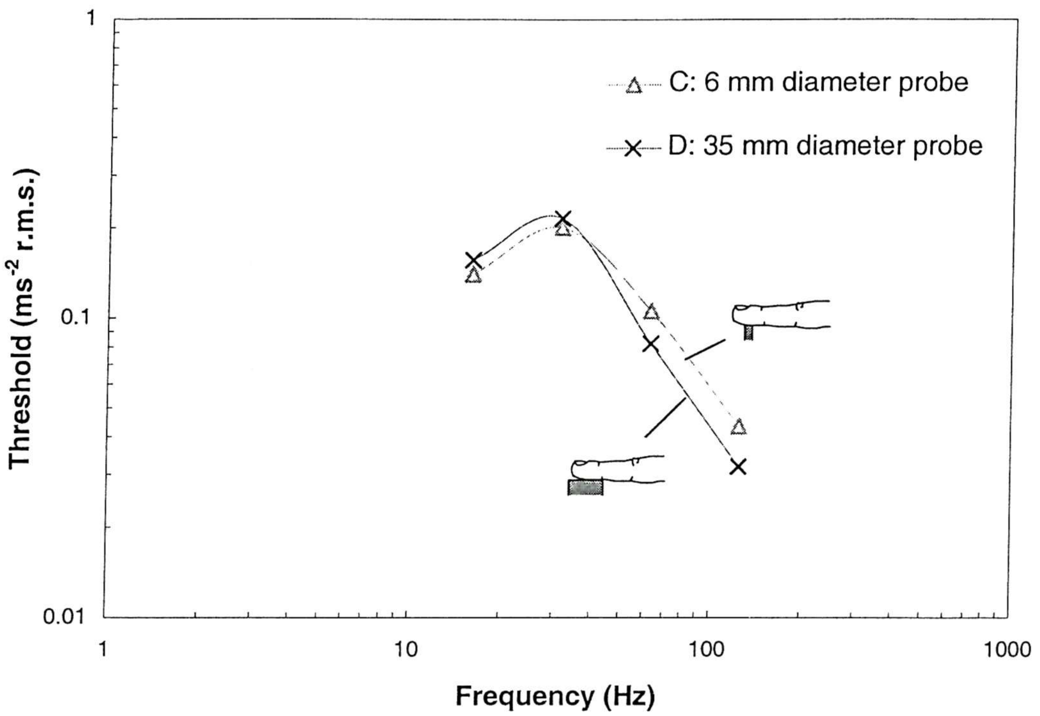


Figure 6-4 Effect of contact area at the distal phalanx of the middle finger. (Median thresholds for 12 subjects) Contact force = 1 N

6.3.4.2 From the fingertip to the whole hand

Figure 6-5 shows median thresholds measured with contact locations from the fingertip to the whole hand (*Conditions E, F, G* and *H*). Thresholds generally decreased with increasing contact area at both low and high frequencies (Friedman, $p<0.001$). Significant decreases in thresholds were obtained when increasing the contact area from the fingertip to the whole finger (*Condition E* to *Condition F*: $p<0.001$, except for 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 however showed no change or reduced sensitivity at 125 Hz when the contact area increased even more from *Condition G* to *Condition H* (see Figure 6-5) ($p=0.0076$, Wilcoxon). There were no significant differences in thresholds at 16 Hz between *Conditions F, G* and *H* at 16 Hz (Friedman, $p=0.17$).

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

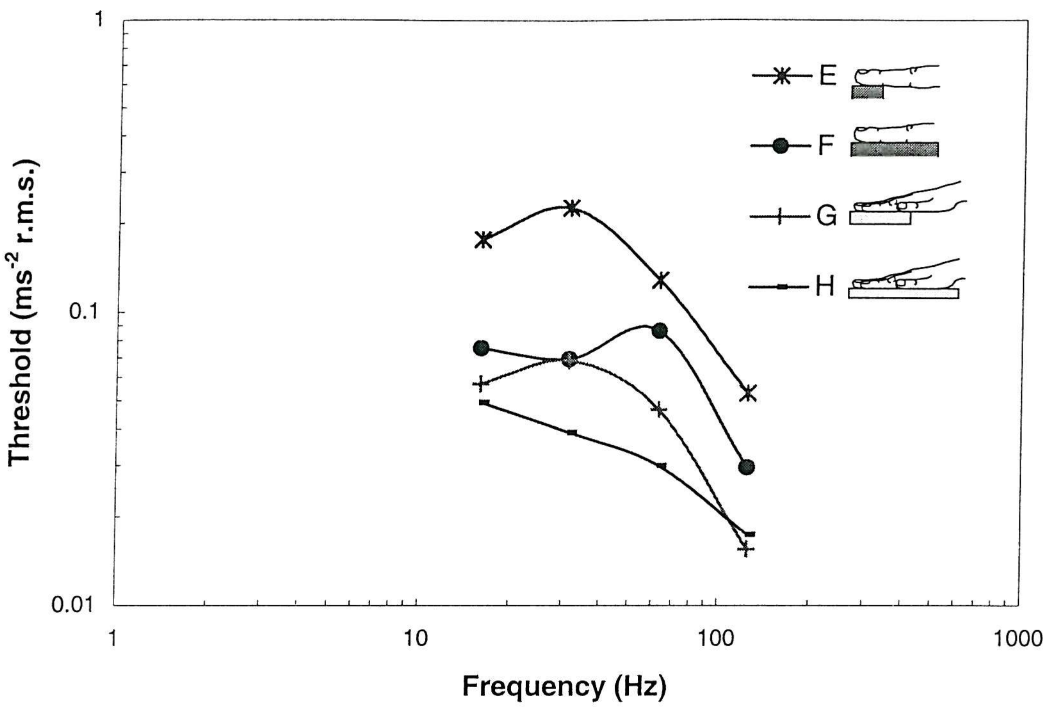


Figure 6-5 Effect of contact area on vibration perception thresholds from the fingertip to the whole hand (Median threshold curves for twelve subjects). Contact force = 5 N.

6.3.5 Overall results

The median vibration perception thresholds were re-plotted as a function of test condition for each frequency (Figure 6-6). The corresponding statistical results are summarised in Table 6-7. The following trends were found: (i) thresholds were strongly affected by a surround around the probe, (ii) at low frequencies, the detection sensitivity was independent of both contact area and contact force at the fingertip, greatly decreased when the contact area included of proximal region of the finger, then gradually increased as the contact area extended to other regions of the hand, (iii) at high frequencies, detection sensitivity was dependent on contact area and contact force.

The individual results for each subject are shown in Figures 6-8 to 6-12 according to the effect of surround, contact area, contact force and contact location.

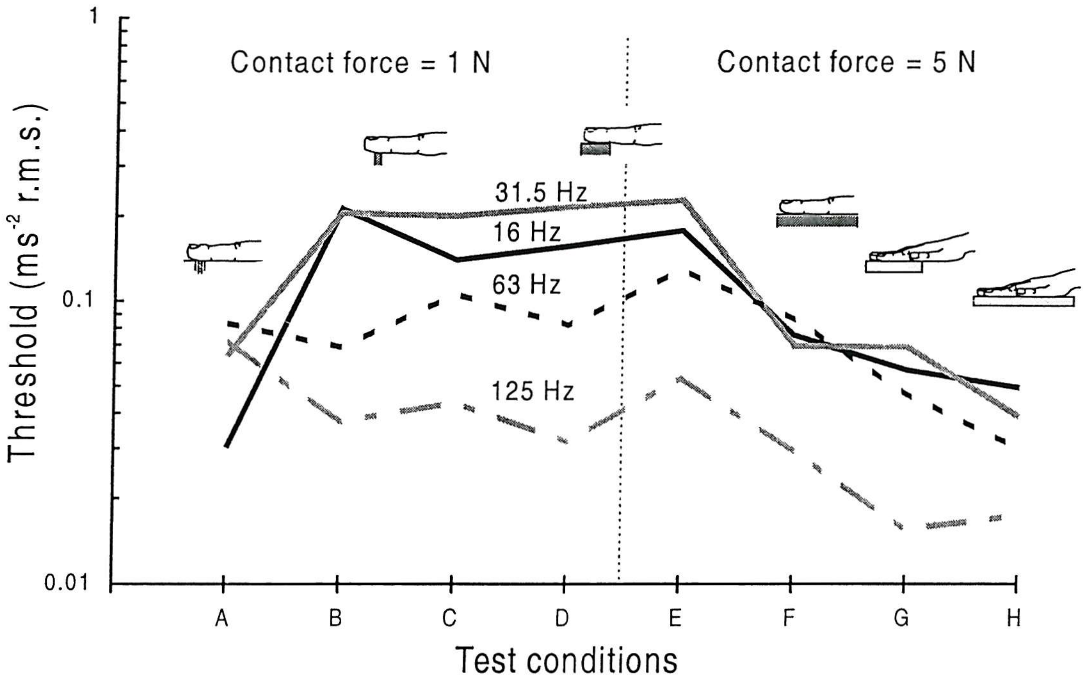


Figure 6-6 Summary results of median thresholds for twelve subjects obtained by eight test conditions.

Table 6-7 Summary of statistical results on vibration perception thresholds.

	Vibration stimulus frequency			
	16 Hz	31.5 Hz	63 Hz	125 Hz
Surround (*Conditions A×B×C*)	↓↓↓	↓↓↓	–	↑↑
Contact force: 1 → 5 N (*Conditions D×E*)	–	–	–	↑
Contact area	–	–	–	
Between fingertip (*Conditions C×D*)	–	–	–	↓
Between fingertip and finger (*Conditions E×F*)	↓↓↓	↓↓↓	-	↓↓
Between finger and hand (*Conditions F×G×H*)	–	↓↓↓	↓↓↓	↓↓↓

↑ increase of threshold; – no change; ↓ decrease of threshold;
* the number of appearing arrows corresponds to the significance level.
(i.e. ↑ $p < 0.05$, ↑↑ $p < 0.01$, ↑↑↑ $p < 0.001$)

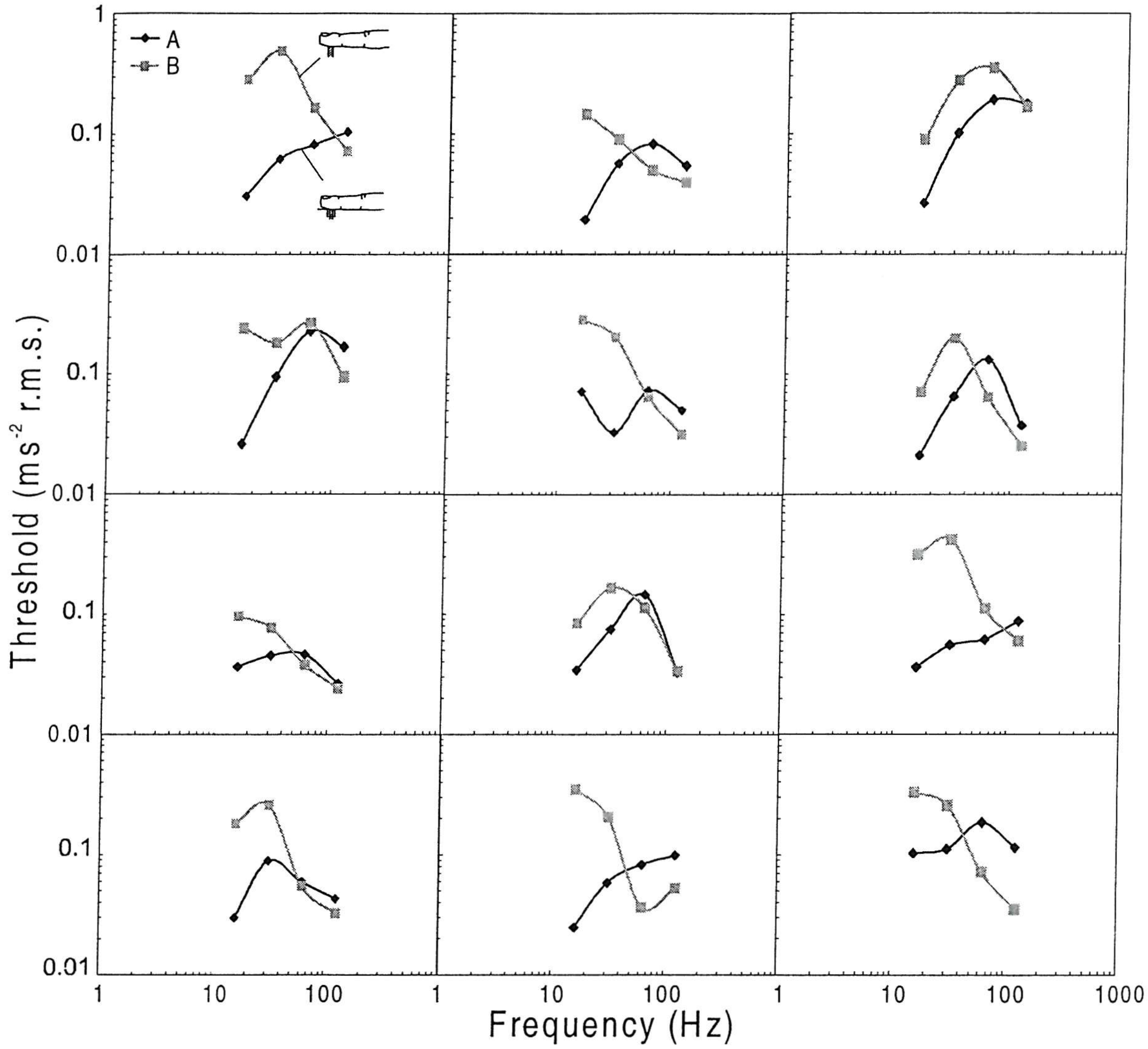


Figure 6-8 Individual thresholds of twelve subjects obtained in Condition A (surround) and Condition B (no surround). *Contactor diameter = 6 mm, Surround diameter = 10 mm, Contact force = 1 N

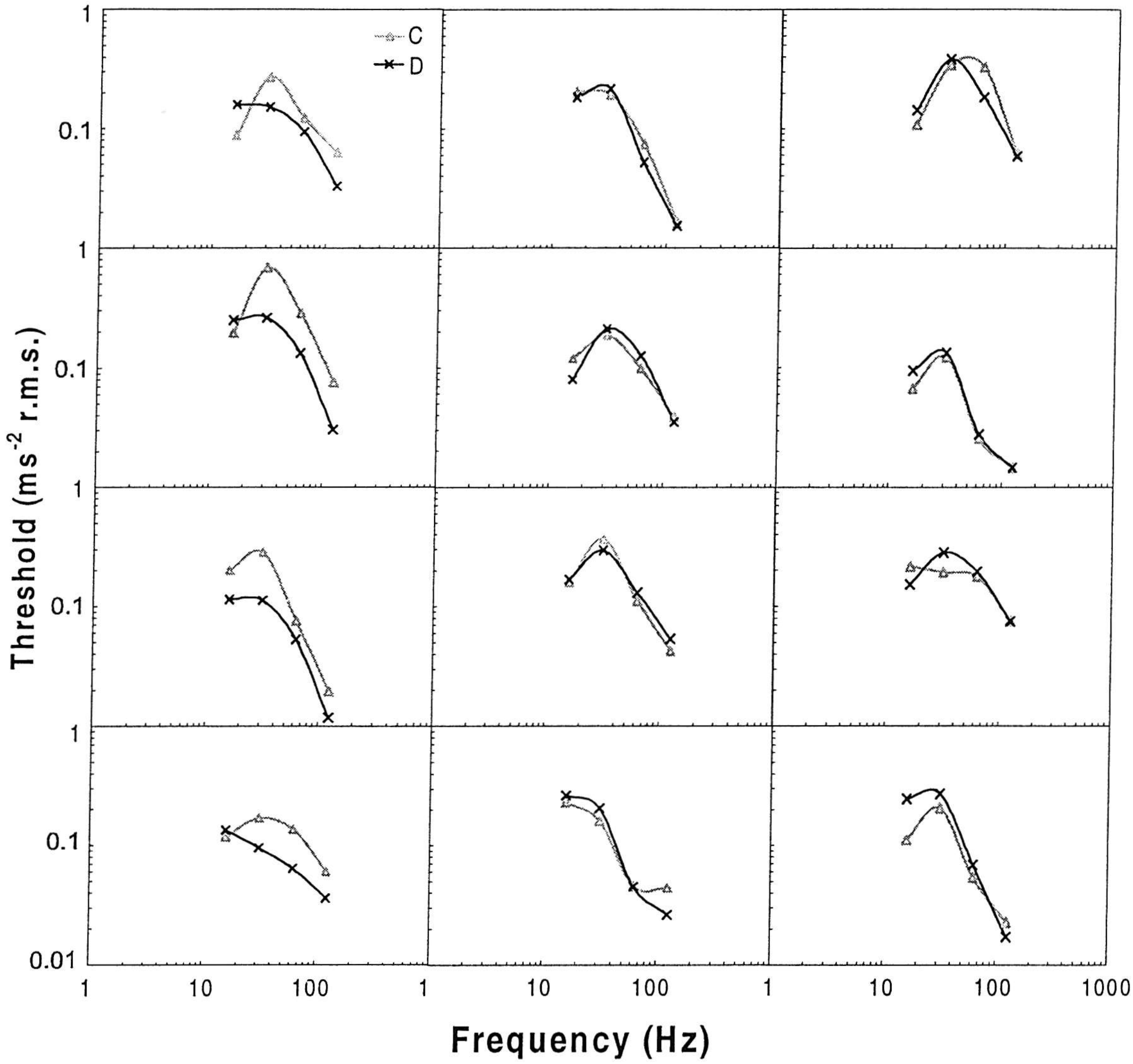


Figure 6-9 Individual thresholds of twelve subjects obtained in Condition C (6 mm diameter circular probe with no surround) and Condition D (35 mm diameter circular probe). * Contact force = 1 N

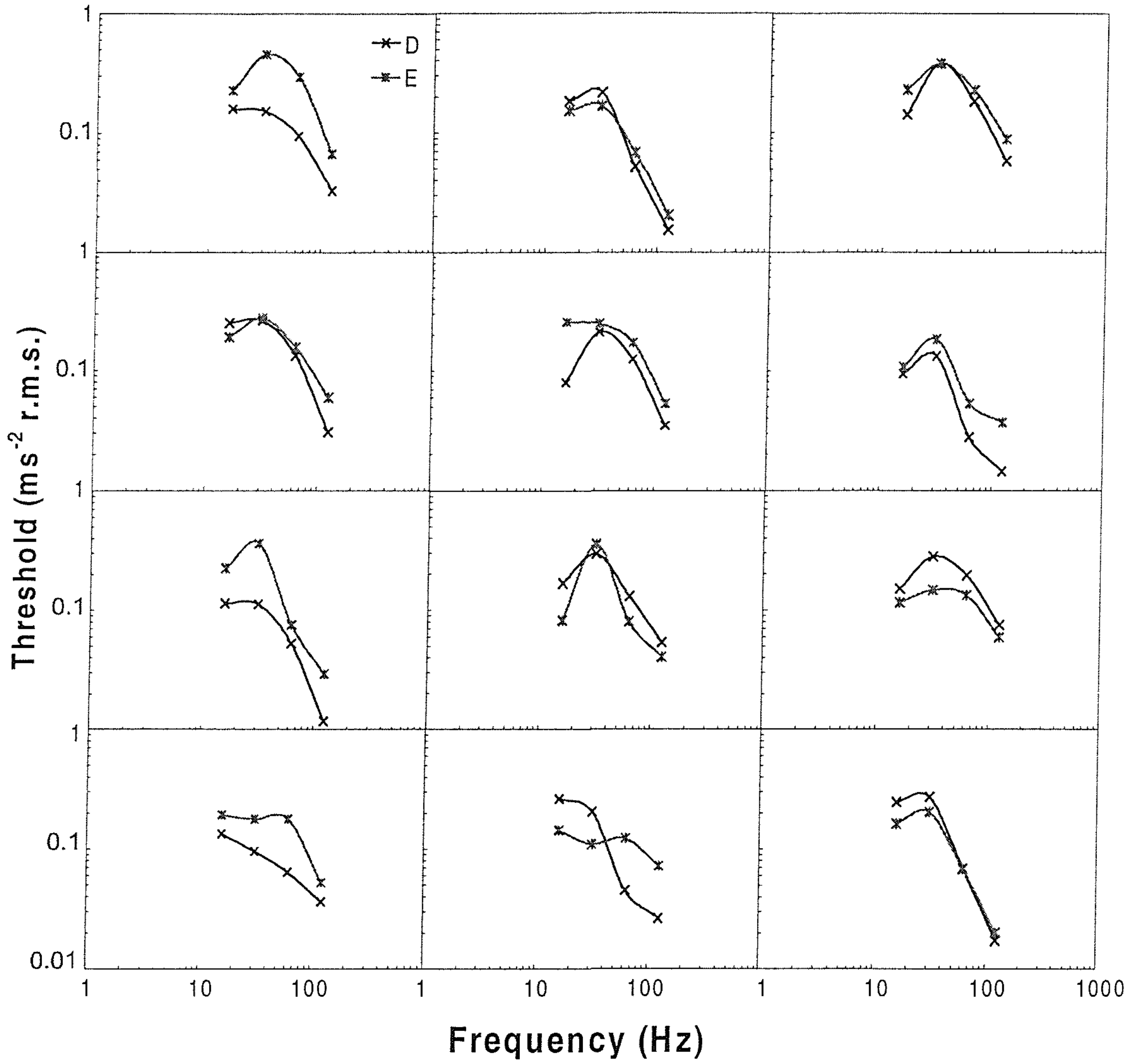


Figure 6-10 Individual thresholds of twelve subjects obtained in Condition D (1 N contact force) and Condition E (5 N contact force). *Contactor diameter = 35 mm

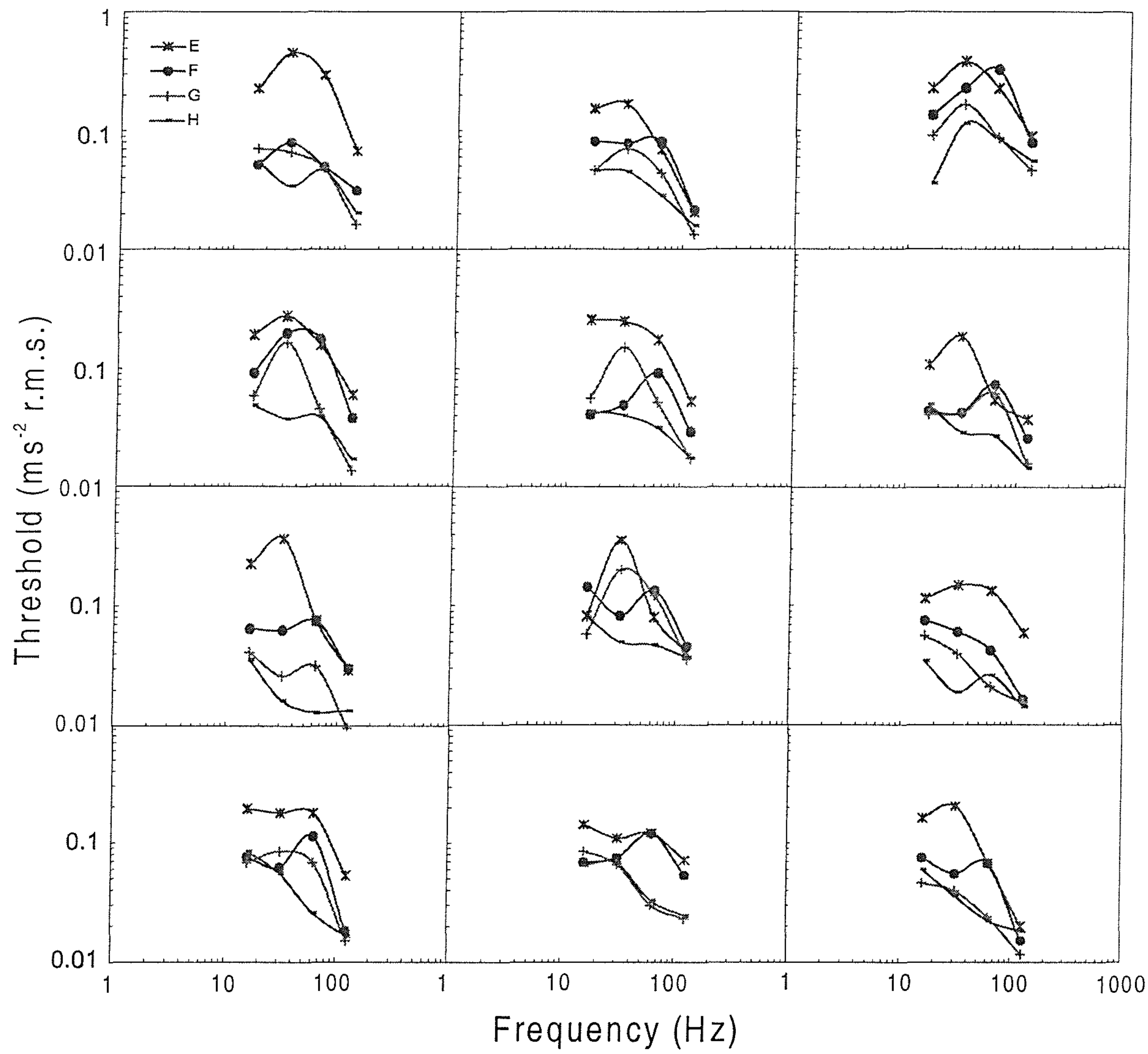


Figure 6-11 Individual thresholds of twelve subjects obtained by Condition E (Fingertip), F (A whole finger), G (Four fingers) and H (Whole hand). *Contact force = 5 N

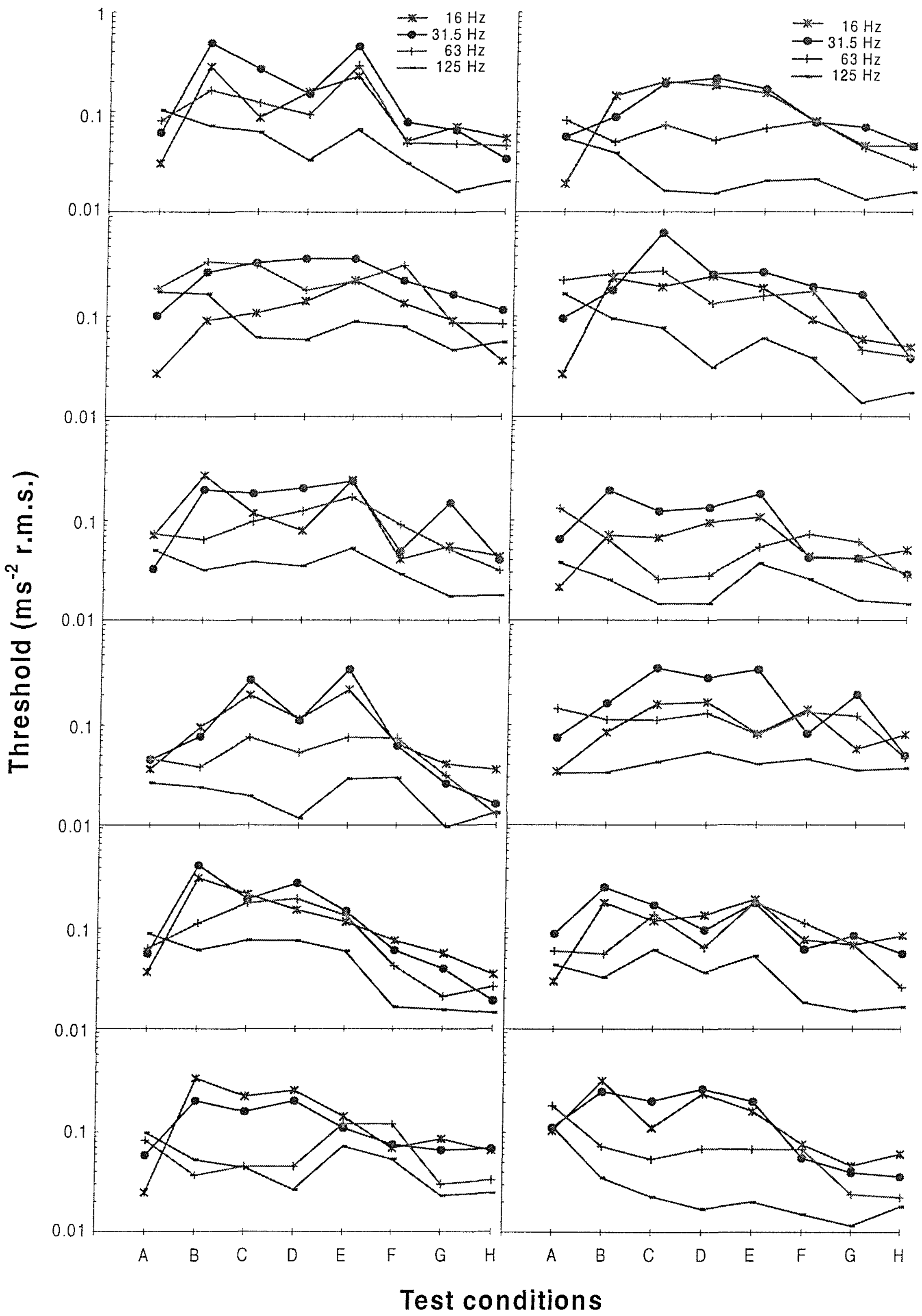


Figure 6-12 Individual thresholds of twelve subjects as a function of test conditions.

6.4 DISCUSSION

6.4.1 Effect of surround

The presence or absence of a surround influenced vibration perception thresholds at the distal phalanx of the middle fingers; the surround caused a decrease in sensitivity at 125 Hz and an increase in sensitivity at 16 and 31.5 Hz (see Figure 6-2). This indicates the involvement of two different mechanoreceptive systems in the response, Pacinian and non-Pacinian systems. The Pacinian system has the capability of spatial summation. The non-Pacinian system has a high sensitivity to gradient stimuli (Verrillo, 1985).

The present results are explained and supported by the results from other studies; Verrillo (1966b) demonstrated that the removal of a surround elevated thresholds at low frequencies, and eliminating the response of a non-Pacinian system. Gescheider *et al.* (1978) proposed that the removal of a surround allows the spreading of vibration over the skin, causing the functional equivalent to increasing the contact area. Verrillo (1979c) examined with different sizes of surround and showed that thresholds at 25 Hz increased as the gap distance increased. He later concluded that there is modification of energy distribution for the non-Pacinian systems with changes in gradient on the surface of the skin (Verrillo, 1985). It was suggested that removal of the surround enhanced the mediation by the Pacinian system at high frequencies, the presence of the surround enhanced mediation by the non-Pacinian receptor systems at low frequencies.

6.4.2 Effect of contact area and contact location

A main finding from the present study was that the vibration perception thresholds decreased with increasing contact area, from the fingertip to the whole hand. As expected, spatial summation seemed to be present with hand-transmitted vibration at high frequency, but also at low frequencies. This was possibly caused by the response of the Pacinian system at low frequency as well as at high frequency, lowering thresholds with increasing contact area.

Even if it were assumed that the Pacinian system is responsible for thresholds of perception of hand-transmitted vibration at most frequencies, there may be other factors lowering thresholds with increasing contact area. Vibration perception may be influenced by the location of the part of the hand in contact with the vibrating surface. Figure 6-13 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 proposed by Verrillo (1963), the results do not show a proportional decrease in threshold with increasing contact area. The contact area approximately doubled when the contact location was extended from the fingertip to the whole finger. This produced a larger decrease in the thresholds at low frequencies than at high frequencies. The thresholds for *Condition D* (whole finger), expressed as a percentage of the thresholds for *Condition C* (fingertip), are: 43% at 16 Hz, 30% at 31.5 Hz, 67% at 63 Hz and 56% at 125 Hz.

Two types of response function can be observed, with different effects at low frequencies (16 and 31.5 Hz) and at high frequencies (63 and 125 Hz). The thresholds at two high frequencies (i.e. 63 and 125 Hz) were correlated (Spearman, $p<0.05$), while no correlation was found at low frequency. This may imply that the same neural excitation was produced by the vibration stimuli at 63 and 125 Hz, which is possibly due to the Pacinian system. It also suggests that low thresholds might partly arise from excitation in areas having superior sensitivity for the detection of the vibration stimuli.

Another contributing factor may be the transmission of vibration within the hand, resulting in excitation, and possibly spatial summation, at locations distant from the area of contact with the vibrating surface. Vibration may have been transmitted to the palm area when the contact location was closer to the palm. Thresholds decreased greatly when contact with the vibrating surface was made by the whole finger (*Condition F*) compared to the fingertip (*Condition E*), but there was less change as contact extended from four fingers to the whole hand (*Condition G* to *Condition H*). An effect of transmission would be partly consistent with the findings of Brisben *et al.* (1999). They determined absolute thresholds at 40 and 300 Hz with various contact conditions when applying a 32 mm diameter cylinder to the glabrous skin of the hand. The interesting findings were: contact with two fingers lowered the thresholds compared to a single finger; the closer the contact location to the palm, the lower the thresholds, even when contact area was little changed.

The extent of vibration transmission within a finger and hand will depend on frequency. This will result in a frequency-dependent effect of contact location if there is either spatial summation or differences in sensitivity with location. For example, with vibration of the whole finger (*Condition F*) the receptors excited by vibration are unlikely to have been only those in the skin in contact with the vibrating surface. The whole volume of the finger (and possibly some of the hand) may have experienced sufficient vibration to excite Pacinian or other receptors.

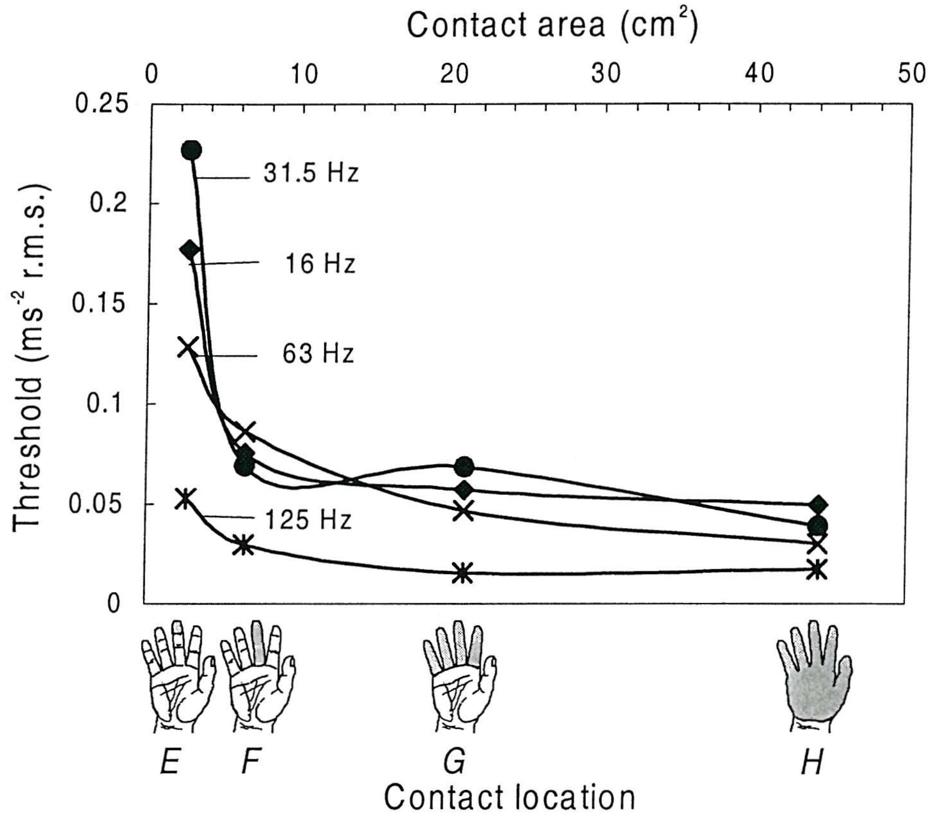


Figure 6-13 Median thresholds for 12 subjects as a function of contact area and contact location.

6.4.3 Effect of contact force

Static force might also affect spatial summation. The present results showed that increased contact force (1 to 5 N) increased thresholds at 125 Hz. This differs from the reduction in thresholds with increased force (1 to 3 N) above 125 Hz found by Harada and Griffin (1991) when using a surround around a contactor. Lamoré and Keemink (1988) suggested that the static force for maximum sensitivity corresponded to a contact pressure of 0.47 N/cm^2. The contact force applied in *Condition E* (1.91 N/cm^2) may have been greater than optimum for mediation via the Pacinian system. Craig and Sherrick (1969) examined the effect of spatial summation on thresholds while holding contact force, contact penetration or contact pressure constant. They found that the spatial summation effect was stronger with constant contact pressure than with constant contact force. It seems the contact force will contribute some change in thresholds, but that change of pressure is insufficient to explain the reduced thresholds with increasing contact area.

6.5 CONCLUSIONS

Absolute thresholds were significantly influenced by a surround at the fingertip, and also highly dependent on contact area, and possibly contact location, while systematically extending the contact area from the fingertip to the whole hand. It seems that the non-Pacinian system did not respond when the surround was removed. It is therefore suggested that the Pacinian system was dominant for mediation of hand-transmitted vibration. Unexpectedly, the results contained an inconsistent spatial summation over the frequency range and over the contact area. Three alternative explanations were produced: (a) sensitivity differences between the hand locations, (b) vibration transmission effects, and (c) responses by other receptors or other factors. Each led to a further voyage for the next discoveries.

CHAPTER 7

STUDY 4 ABSOLUTE THRESHOLDS: VARIATION IN SENSITIVITY OVER THE GLABROUS HAND

7.1 INTRODUCTION

A previous study (Chapter 6) found a spatial summation effect with absolute thresholds at both low frequencies and high frequencies: a decrease in thresholds with increasing contact area from the fingertip to the whole hand. One of the possible explanations for the finding was that lower thresholds were obtained with the larger contact area because some locations in the hand may have greater sensitivity to the vibration stimuli. The larger contact area would contain more sensitive locations, which could result in lower thresholds.

A follow-up study was carried out to examine whether vibrotactile thresholds vary between various locations on the glabrous skin of the hand exposed to the vibration.

Regional differences in vibration perception on the hand have been investigated in a few previous studies. Roland and Nielsen (1980) determined absolute thresholds at 100 Hz at eight points on the glabrous skin of the hand using a 13 mm diameter contactor with a large population of normal and patient subjects. They found that the thresholds depended on the location of stimulation, but were more influenced by age and sex. Löfvenberg and Johansson (1984) measured absolute thresholds with a 6 mm diameter contactor at seven points on the glabrous part of the hand. Lundström (1984a) conducted a similar study using a 9 mm diameter contactor. These findings are not conclusive, as a surround was not used for threshold determinations: the dependence of vibrotactile thresholds on a surround is well known to affect responses of both Pacinian and non-Pacinian systems. The absence of a surround may have failed to produce a sufficient response of the non-Pacinian system, or allowed a sufficient spreading of vibration over the skin in the vicinity of the contactor to produce spatial summation via the Pacinian system. It is known that the non-Pacinian responses are sensitive when applied a surround (Gescheider. *et al.*, 1978)

No study has yet applied a surround for examining regional difference in sensitivity for both the Pacinian and the non-Pacinian systems over the glabrous skin of the hand.

In this study, vibrotactile thresholds were measured using a circular probe with a surround (*HVLab* Tactile Vibrometer, see the details in Chapter 3) determining at eight different locations over the glabrous skin of the hand. Four stimulus frequencies (i.e., 16, 31.5, 63 and 125 Hz) were chosen in order to elicit the response of both Pacinian and non-Pacinian systems.

7.2 EXPERIMENTAL DESIGN

7.2.1 Subjects

Twelve healthy males, aged 22 to 32 years (mean 25.9 years), participated in the experiment. Finger skin temperature at the distal part of the middle finger was measured prior to the experiment. Threshold measurements proceeded if the temperature was above 29° Celsius.

7.2.2 Threshold measurements

Vibration perception thresholds were determined at eight locations on the glabrous skin area of the right hand, repeated with four frequencies (16, 31.5, 63 and 125 Hz). The locations of the test points are shown in Figure 7-1. The test locations on the hand were marked using a pen in order to make sure that the repeated measurements were performed at the same location. The *HVLab* Tactile Vibrometer was employed to measure vibrotactile thresholds (the same equipment and contact condition as Algorithm A described in the Section 4.2.3). The upward contact force from the contact probe was set at 0.5 N as some

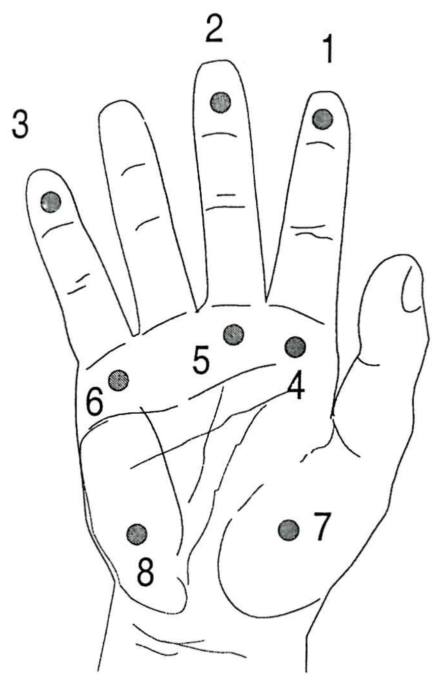


Figure 7-1 Location of eight test points on the glabrous skin of the hand.

particular location has a difficulty to get an exact contact at 1.0 N. Table 7-1 provides a summary of experimental conditions employed in this study.

The threshold measurements were performed in one session. All test points were examined in random order.

Table 7-1 Summary of experimental conditions.

Subjects	
Number (N=)	12 males
Age	22-32 years (mean 25.9 years)
Height	
Weight	
Test stimuli	
Frequency	16, 31.5, 63 and 125 Hz
Duration	30 seconds (continuous stimuli)
Skin-simulator contact	
Probe diameter	6 mm diameter
Probe-surround gap	2 mm
Contact force (upward)	0.5 N
Push force (downward)	2 N
Algorithm	
Psychophysical method	Békésy
Initial step rate	5 dB/s
Testing step rate	3 dB/s
Reversals	At least 6 reversals (6 peaks and 6 troughs)
Subject response	automatic (using a stop button)
Temperature	
Finger skin temperature (FST)	29 - 34 °C
Room temperature	22 - 24 °C

7.3 RESULTS

7.3.1 Effect of contact location on the hand (overall results)

Vibrotactile acceleration threshold contours as a function of frequency from 16 to 125 Hz were obtained for each test location. Figure 7-2 shows median threshold contours of twelve subjects for eight test points. The thresholds varied between the eight test points; the highest thresholds were a factor of between 1.9 and 2.2 (i.e. 5.4 and 7.0 dB) greater than the lowest thresholds (see details in Table 7-2). Overall, the shapes of the threshold contours for the eight test points were similar; low thresholds at the lowest frequency (i.e. 16 Hz), and relatively high thresholds at the higher frequencies (63 and 125 Hz). Individual subject data for each measured frequency are shown in Figure 7-3. The thresholds varied between subjects, but clear trends can be seen. At low frequencies (16 and 31.6 Hz), thresholds tended to get the lowest at distal part of the finger (points 1, 2, and 3) compared with the other points. At the highest frequency (125 Hz), thresholds were virtually unchanged or slightly lower at the distal part of the palm (points 4, 5, and 6). The trends can be observed in Figure 7-4, in which its median thresholds from distal to proximal points are compared.

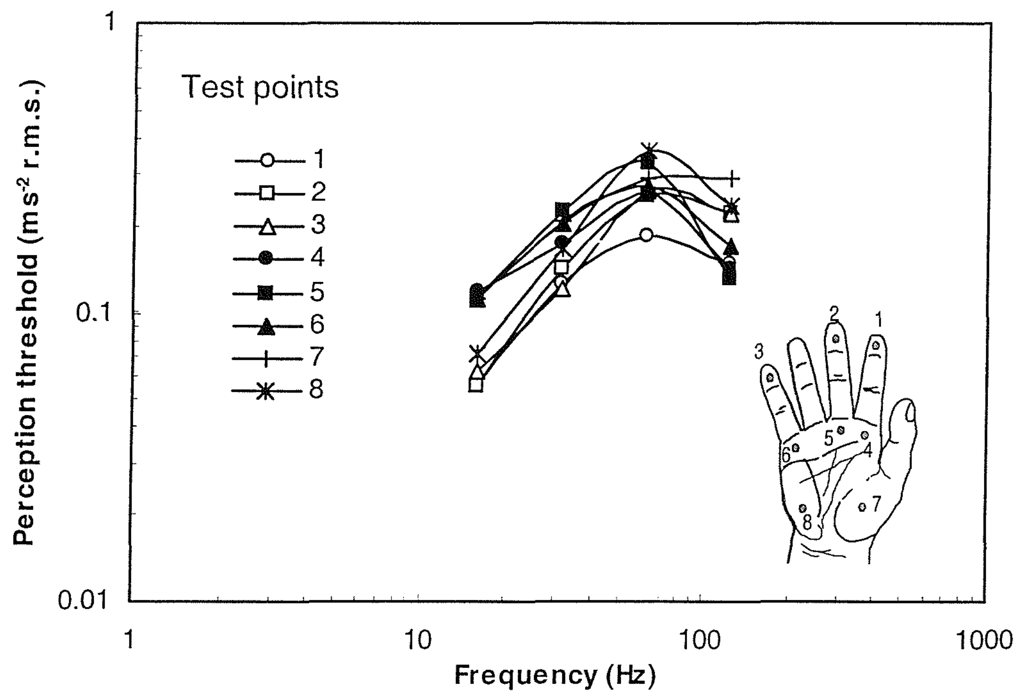


Figure 7-2 Median thresholds of twelve subjects obtained at 8 test points.

Table 7-2 Summary of median thresholds for the eight test points.

	16 Hz	31.5 Hz	63 Hz	125 Hz
Mean of 8 points	0.087	0.171	0.277	0.194
SD of 8 points	0.028	0.039	0.054	0.056
Max (test point)	0.119 (p4)	0.224 (p5)	0.364 (p8)	0.291 (p7)
Min (test point)	0.055 (p1)	0.120 (p3)	0.182 (p1)	0.130 (p5)
Max/Min	2.16	1.87	2.00	2.24
Max/Min (in dB)	6.67	5.42	6.01	7.00

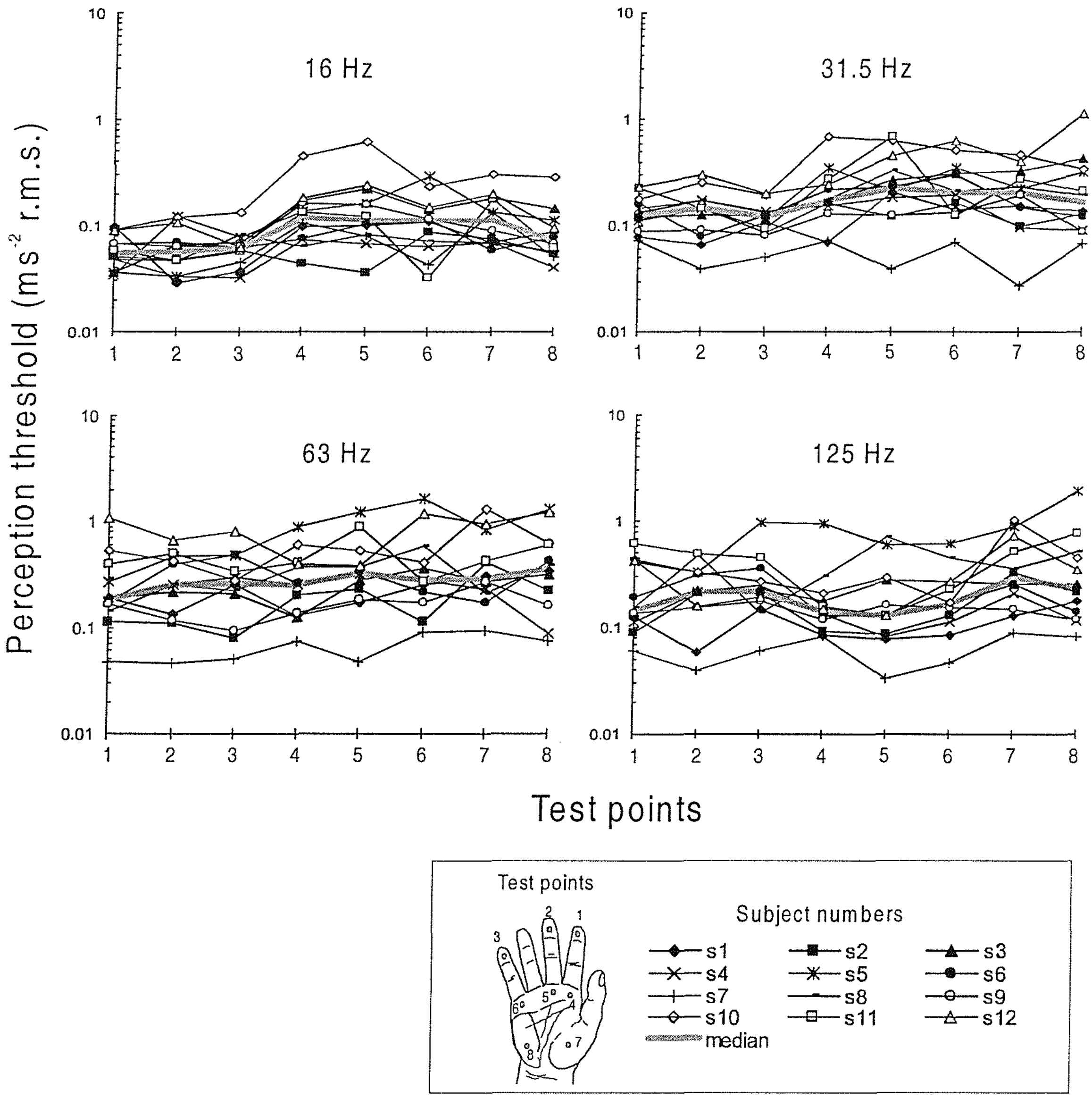


Figure 7-3 Perception thresholds of twelve subjects as a function of test point measured at four test frequencies. The grey lines are median thresholds

Statistical tests were applied to test the hypotheses. There were no differences in thresholds between the three distal parts of the fingers (i.e. test points 1, 2 and 3; Friedman, $p>0.2$), between three points on the distal part of the palm (i.e. test points 4, 5 and 6; Friedman, $p>0.15$), or between two points at the proximal part of the palm (i.e. test points 7 and 8; Wilcoxon, $p>0.4$, except for 16 Hz, $p=0.008$). At 16, 31.5 and 63 Hz, the lowest thresholds were obtained on the distal parts of the fingers (i.e. at test points 1, 2 and 3).

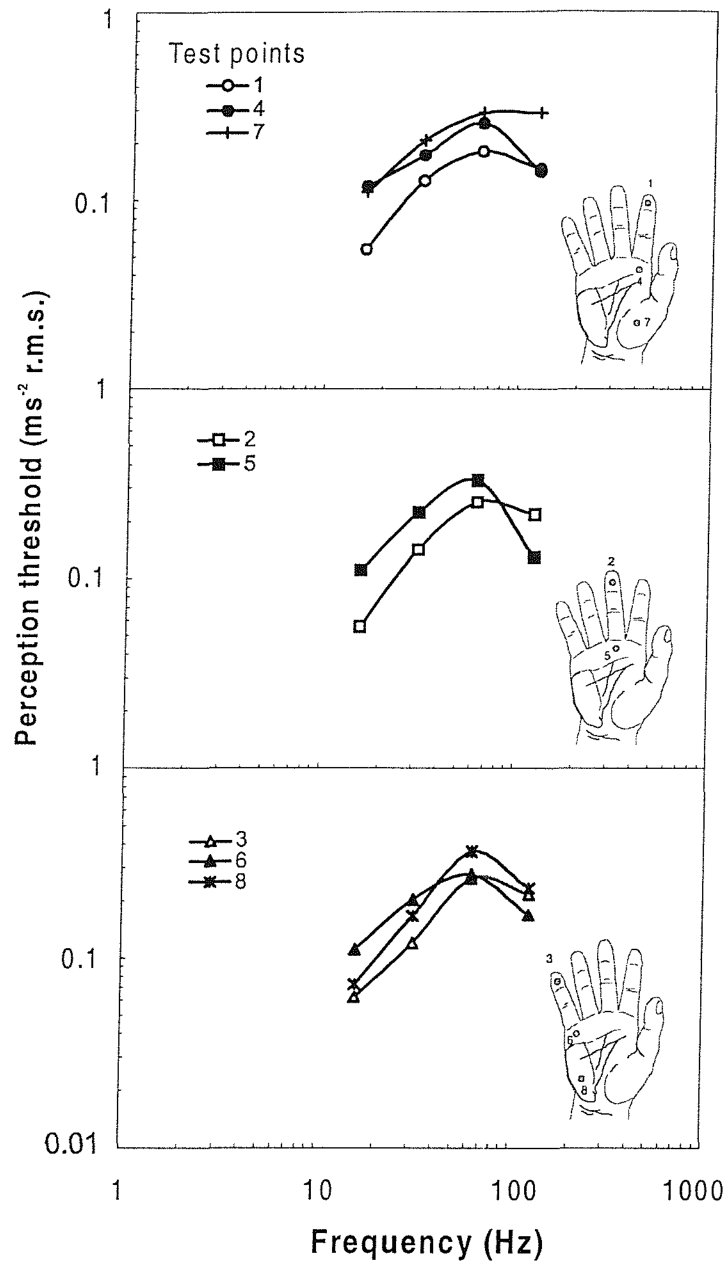


Figure 7-4 Median vibration perception thresholds for eight test points as a function of frequency: data separated to compare different test locations.

The differences in thresholds between the distal finger and the distal palm were statistically significant at only 16 and 31.5 Hz (Wilcoxon, $p<0.05$). The differences in thresholds between the distal finger and the proximal palm were significant at 16, 31.5 and 63 Hz. An unexpected tendency was observed with thresholds at 125 Hz: eight of the twelve subjects gave the lowest thresholds at the distal palm. At 125 Hz, the thresholds at the distal finger were not significantly different from those of the distal palm (Wilcoxon, $p>0.05$), but significantly greater than those at the proximal palm (Wilcoxon, $p<0.05$).

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

7.3.2 Effect of test finger and test location

Further analysis has been carried out, focusing on the perception thresholds at the distal fingers and the distal palm. The perception threshold data were re-plotted according to the test finger and the test locations as shown in Figure 7-5. Almost the same threshold was obtained on each test finger, but it seemed the threshold depended on the test location (i.e. the distal part of a fingers or the distal part of the palm: locations A and B in Figure 7-5). The ratios of the thresholds at the distal palm to the thresholds at the distal finger for each frequency were 1.98, 1.54, 1.25 and 0.76, at 16, 31.5, 63 and 125 Hz, respectively. Repeated measures analysis of variance (ANOVA) was employed for testing within-subjects factors (i.e., 3 test fingers, 2 test locations and 4 stimulus frequencies), and the results are shown in Table 7-3. The effect of contact location and stimulus frequency was significant with *p* values of 0.04 and 0.002, respectively, but there was no effect of test finger (p=0.371). A marginal interaction between the test frequency and the test location was found (p=0.083). It seems that this was caused by a reversal of thresholds at 125 Hz, as can be seen in Figure 7-6.

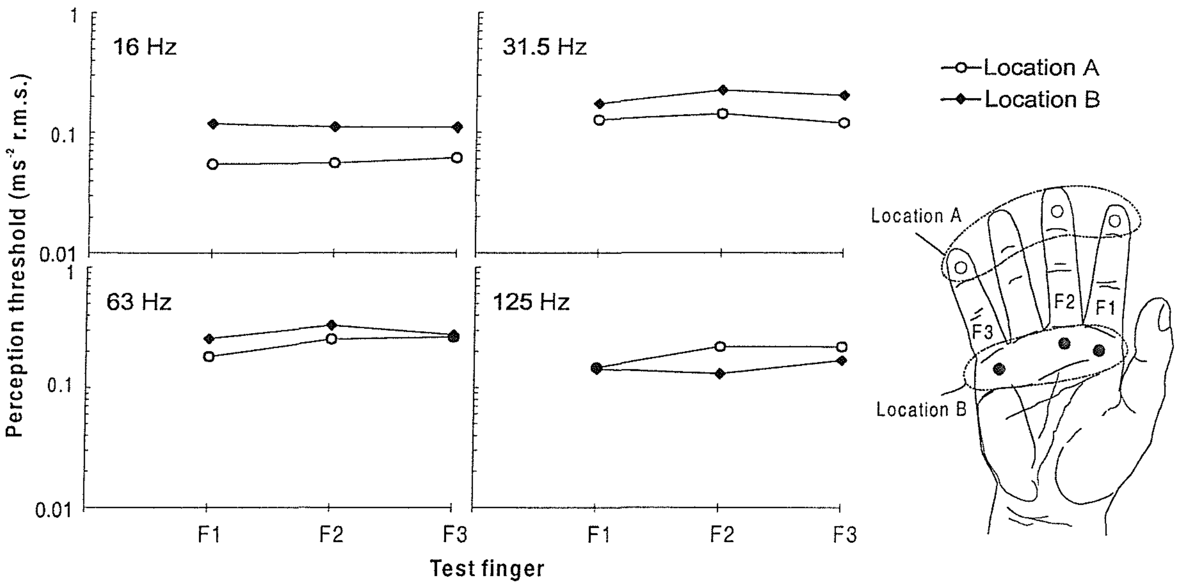


Figure 7-5 Effect of test finger (index, middle and little finger) and test location (distal part of the fingers and distal part of the palm) for four frequencies. Median values of twelve subjects are shown.

Table 7-3 Analysis of variance within-subjects effects of test location (location A and B), test finger (F1, F2 and F3), stimulus frequency (16, 31.5, 63 and 125 Hz). Greenhouse-Geisser test was used for the analysis due to the.

Source	Sums of squares	Degrees of freedom	Mean square	F ratio	Sig.
Location	0.332	1	0.332	5.413	0.040 *
Error (Location)	0.674	11	0.062		
Finger	0.046	1.5	0.031	0.978	0.371
Error (Finger)	0.512	15.9	0.032		
Frequency	2.217	1.7	1.296	9.737	0.002 **
Error (Frequency)	2.504	18.8	0.133		
Location*Finger	0.024	1.7	0.013	0.773	0.456
Error (Location*Finger)	0.319	18.7	0.017		
Location*Frequency	0.287	1.8	0.158	2.894	0.083
Error (Location*Frequency)	1.091	20.0	0.055		
Finger*Frequency	0.057	3.0	0.019	0.883	0.460
Error (Finger*Frequency)	0.704	32.9	0.021		
Location*Finger*Frequency	0.055	2.4	0.023	0.460	0.399
Error (Location*Finger*Frequency)	0.606	26.0	0.023		

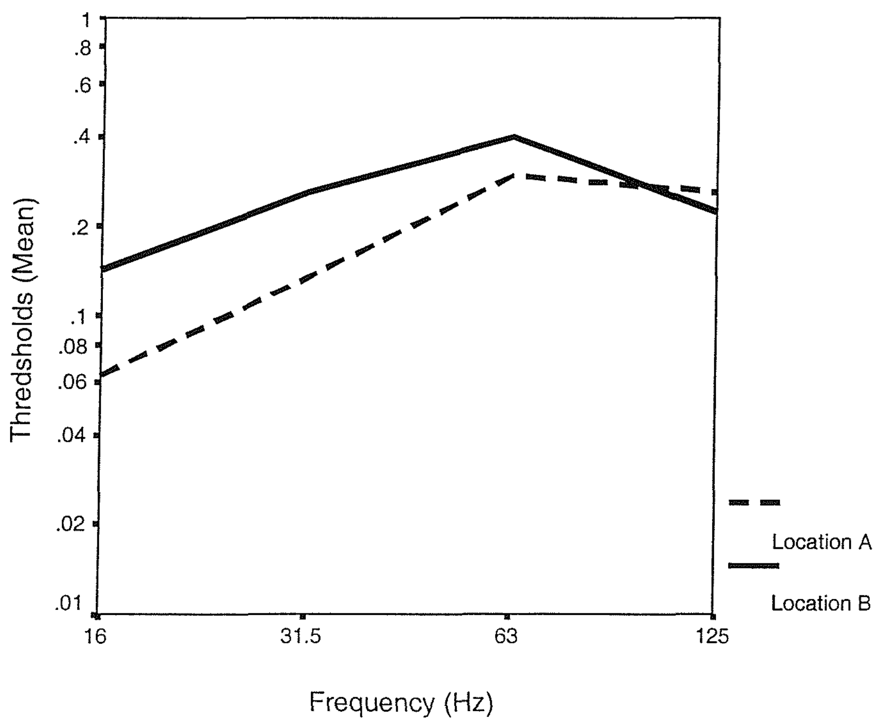


Figure 7-6 Interaction of thresholds between test frequency and test location.

7.4 DISCUSSION

Vibration perception thresholds varied with test location on the glabrous skin of the hand, showing an independence of test finger but difference between the hand and fingers. Summary threshold data for the eight test points are presented in Figure 7-7. There is a reversal in perception thresholds between low and high frequencies: the distal fingers (points 1, 2 and 3) were more sensitive than the distal palm (points 4, 5 and 6) at low frequencies (i.e. 16, 31.5 and 63 Hz), but less sensitive at high frequencies (i.e. 125 Hz).

7.4.1 Comparison with other studies

The findings are partially consistent with the results from similar studies, indicating location dependence in thresholds at low frequencies, but less dependence at high frequencies. Roland and Nielsen (1980) found no significant differences in thresholds at 100 Hz over the glabrous area of the hand, with the exception of the fifth digit (which gave the highest thresholds). The results from Löfvenberg and Johansson (1984) showed location differences below 40 to 60 Hz (a decrease in thresholds from proximal to distal areas), but less difference above 40 to 60 Hz. Lundström (1984) observed that the greatest vibrotactile sensitivity was on the tips of the fingers and the thumb at both 25 Hz and 100 Hz. The thresholds from Lundström (1984a) have been modified and are illustrated in Figure 7-8 to allow comparison with the present results. Large differences of thresholds between the two results are observed, thresholds from Lundström (1984a) are more than a factor of 5 higher than the thresholds from the current study. This could be due to the different conditions of skin-stimuli contact (e.g., contact area and surround) employed in the studies. Also the Lundström's study employed a high step rate (10 dB/s) for measuring vibrotactile thresholds, which might have influenced absolute thresholds value if considering the reaction time between the detection of a stimulus and pressing the response button. Nevertheless, the interesting finding is that the thresholds were slightly lower in the distal palm area than at the other areas measured at frequencies between 25 and 100 Hz, similar to the finding from the present study.

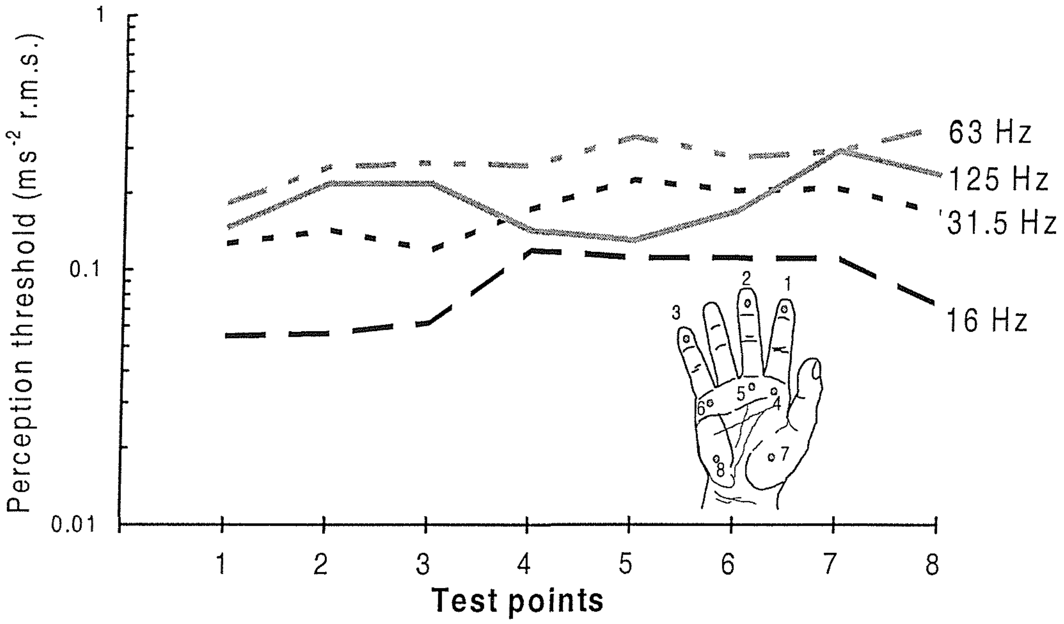


Figure 7-7 Summary of median vibration perception thresholds as a function of frequency at eight test points.

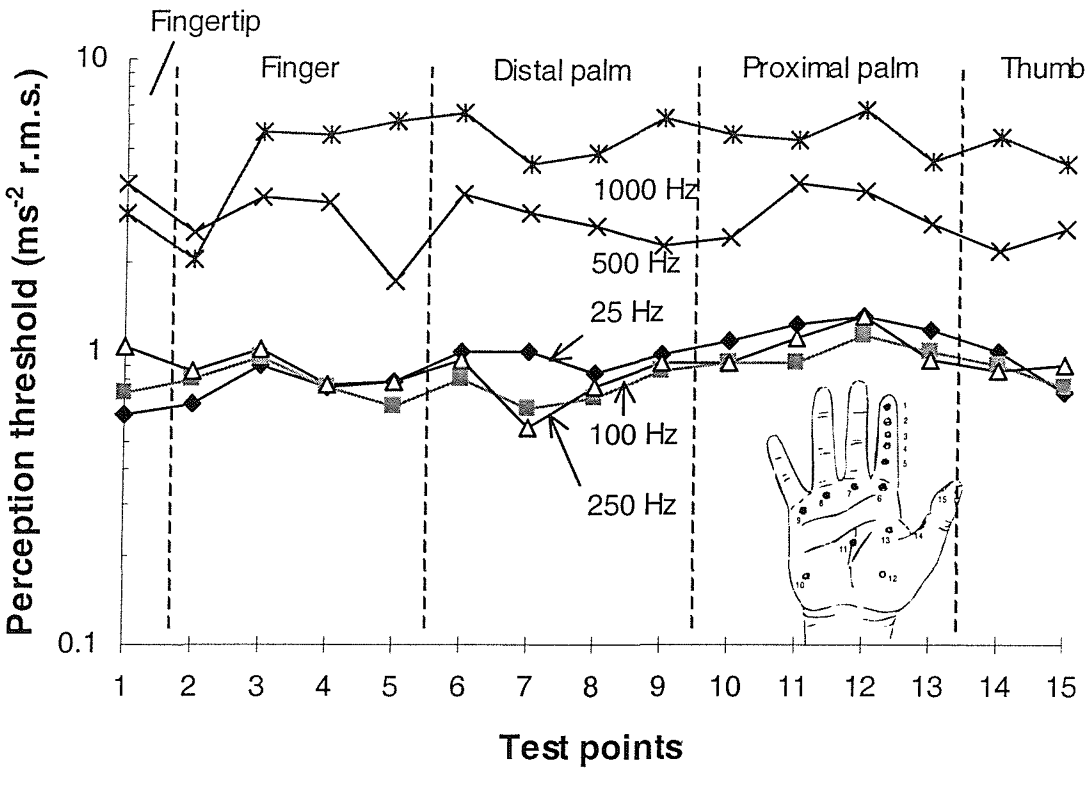


Figure 7-8 Results from Lundström (1984), perception thresholds for fifteen test points on the glabrous region of the hand. Threshold value transposed to acceleration from velocity.

7.4.2 Response of Pacinian and non-Pacinian systems

According to the 'gradient theory', the response to vibration at low frequencies (i.e. below 30 to 40 Hz) is dominated by the non-Pacinian system when a surround is present: a small gap between a probe and a surround provides a stimulus gradient to elicit the non-Pacinian response. This has been shown 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 examining the effect of a surround at the fingertip or the thenar eminence. At low frequencies (i.e. below 30 to 40 Hz), thresholds decreased when a surround was present (or conversely increased when a surround was absent). In the present study, it is fairly certain that the low frequency vibration stimuli (possibly also the 63 Hz vibration stimulus) were mainly detected via the 'non-Pacinian' system: the thresholds at 16, 31.5 Hz and 63 Hz have similar response characteristics over the test points (see Figure 4). The results therefore indicate that the response of the non-Pacinian system depends on the contact location, with a higher sensitivity at the fingertips than at the distal palm. Löfvenberg and Johansson (1984) obtained results with most sensitivity at distal locations and less sensitivity at proximal locations at low frequencies (below 40 to 60 Hz) and suggested that thresholds are correlated with the density of the receptors. It is known that the non-Pacinian receptors (believed to be dominated by Meissner corpuscles) are highly distributed at the fingertips and less dense at the palm (Johansson and Vallbo, 1979a). However, this explanation is not fully justified; the absolute thresholds at low frequency obtained by Löfvenberg and Johansson (1984) may not have reflected the response of the non-Pacinian system because they did not use a surround and may not have achieved a sufficient gradient.

In respect of the spatial summation of the Pacinian system, previous results suggest a decrease in thresholds proportional to an increase in contact area over the glabrous skin of the hand (e.g. a 3 dB reduction of threshold per doubling of contact area, as proposed by Verrillo 1963). Brisben *et al.* (1999) 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 were not proportional to the contact area but were dependent on contact location: the closer to the palm or the distal palm, the lower the threshold. Similar findings were obtained in a previous study (see section 4.3) when examining the vibration perception thresholds as the contact area increased from a fingertip to the whole hand. The greatest reduction in threshold was obtained when contact with the fingertip was extended to contact with the whole finger, at both low frequencies and at high frequencies.

Alternative explanations for the changes might be considered: thresholds are lowered by contact with the vibration source where the mechanoreceptors have high sensitivity, or thresholds are lowered by contact in an area where transmission of vibration to another part of the hand (e.g. the palm area) allows spatial summation (or greater sensitivity). According to the present findings, differences in thresholds at low frequencies almost contradict an explanation of previous findings based on the fingertip being more sensitive. However, this explanation could be supported on the assumption that the non-Pacinian system may not mediate the perception of hand-transmitted vibration unless a stimulus gradient is produced during contact with a vibrating surface. At high frequencies, the sensitivity of the Pacinian system did not show much change with varying contact locations, although there were lower thresholds at the distal palm at 125 Hz. An effect of contact location might therefore contribute to the spatial summation of hand-transmitted vibration, but it would not be a sufficient explanation of the previous findings.

7.5 CONCLUSIONS

Using an *HVLab* Tactile Vibrometer consisting of a surround around a circular probe, there were no differences in thresholds between three test fingers (i.e. index, middle and little fingers) at each of four frequencies (16, 31.5, 63 and 125 Hz). Differences due to contact location (the distal finger compared with the distal palm) were significant, except for 125 Hz. This finding might imply distinctive responses for the Pacinian and the non-Pacinian systems, suggesting that the 125 Hz of stimuli are likely to be mediated by the Pacinian system, and other frequencies (16, 31.5 and 63 Hz) are likely to be mediated by the non-Pacinian system.

It was suggested that differences in vibrotactile sensitivity were pronounced in perception via the non-Pacinian system, but less pronounced for the Pacinian system. The effects of contact area and contact location should be included in models of the sensory mechanisms responsible for the perception of hand-transmitted vibration.

CHAPTER 8

STUDY 5 SENSATION LOCALISATION INFLUENCED BY CHANGE OF CONTACT AREA

8.1 INTRODUCTION

The previous experiment (Study 4) determined absolute thresholds with various contact conditions. The results verified that contact area contributes to a change in sensitivity, showing great reductions of sensitivity with increasing contact area from the fingertip to the whole finger. The possible explanations included a biodynamic effect: a change in the physical response of the hand due to the change in contact area, which resulted in exciting different receptors at particular areas of the hand. It is possible that the mechanical characteristics of skin and tissues influence psychophysical responses.

Some biodynamic research on hand-transmitted vibration has investigated the transmission of vibration to the various locations on the hand/arm (Reynolds and Angevine, 1977; Maeda *et al.*, 1982; Sörensson and Lundström, 1992; Sörensson and Burström, 1997), absorption of vibration energy in the hand and arm (Burström and Lundstöm, 1994), or mechanical impedance of the hand and arm (Gurram *et. al.*, 1995; Lundström, 1984b). These studies have investigated whether the characteristics of the dynamic responses of the hand and arm influence the injury produced by hand-transmitted vibration. There seems to have seen less attention to the investigation how the dynamic response might influence the sensation response at the hand.

A study by Whitham and Griffin (1978) investigated the locations of areas of discomfort for whole-body vertical and horizontal vibration at 1.0 ms^{-2} at various frequencies (2, 4, 8, 16, 32 and 64 Hz). The area of discomfort experienced in the body moved towards the lower body and the contact with the vibration source (i.e. abdomen and buttocks) with increasing stimulus frequency. The study did not investigate include the effect of changing the exposure area.

It was hypothesised that a change of contact area in the glabrous regions of the hand can influence the location of sensations that give rise to vibration perception.

8.2 OBJECTIVES

In this study, the location of sensations due to hand-transmitted vibration was investigated subjectively in order to examine the effects of:

- Contact condition (i.e. contact location, hand posture)
- Stimulus frequency
- Stimulus intensity

8.3 METHOD

8.3.1 Subjects

Twenty males within the range of 18 to 25 years (mean age 20.4 years) volunteered for this experiment. The subjects had varying backgrounds, with regards to previous vibration exposure, smoking or non-smoking, left or right handed, although most fell into the category of right handed, non-smokers. The hand and middle finger dimensions of the subjects were measured using the same method applied in the previous study (see Section 5.3.2) and are summarised in Table 8-1.

Table 8-1 Body/hand/finger characteristics for twenty subjects.

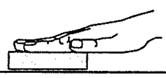
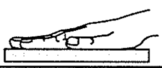
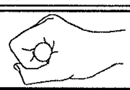
	Height (cm)	Weight (kg)	Hand length (mm)	Hand width (mm)	Middle finger length (mm)	Digital phalanx length of the middle finger (mm)	Digital phalanx width of the middle finger (mm)
Mean	179.9	77.1	192.7	90.7	91.5	28.5	18.7
Minimum	168	62	170	80	80	25	16
Maximum	190	100	209	100	100	32	20
SD	6.23	10.56	10.05	3.59	6.12	3.1	1.17

8.3.2 Stimuli and contact conditions

Sinusoidal vibration at frequencies of 8, 16, 31.5, 63 and 125 Hz, each with a duration of 5.0 seconds were created as test stimuli. The vibration stimuli were generated using a Derritron VP 30 electrodynamic vertical vibrator. The tests were carried out at 2.0 and 4.0 ms^{-2}r.m.s., well above threshold values for the frequency range and contact conditions, according to the results of the previous studies (i.e. Chapters 2 and 6).

Subjects were exposed to the test stimuli with five different contact conditions, varying contact areas and hand postures, as summarised and illustrated in Figure 8-2.

Table 8-2 Contact conditions employed in the experiment. The contactors and the contact conditions were similar to the conditions used in Study 3 for Conditions A, B, C and D and in Study 2 for Condition E.

Condition	Finger or hand posture	Contact location	Dimension of contactor	Contact force
A		Distal phalanx of the middle finger	35 mm diameter Nylon probe	1 N
B		Whole middle finger	22 × 120 mm Plywood plate	1 N
C		Four whole fingers (excluding the thumb)	120 × 120 mm Plywood plate	5 N
D		Whole hand	220 × 150 mm Plywood plate	5 N
E		Whole hand (grasping posture)	30 mm diameter Plywood handle	5 N

For Conditions A, B and C, the contactor was attached to the large plate used for Condition D. A piezoelectric accelerometer (DJ Birchall 747 A/20T) was attached as close as possible to the centre of each of the five contact areas.

During the test, a contact force was controlled at either 1 N (for Conditions A and B) or 5 N (for Conditions C, D and E), which was achieved by attaching a load cell (DS Europe, type LT-0545) on the vibrator, beneath the contact source (plywood plate).

8.3.3 Procedure

The experiment to determine the localisation of the sensations caused by hand-transmitted vibration was carried out with the following procedure.

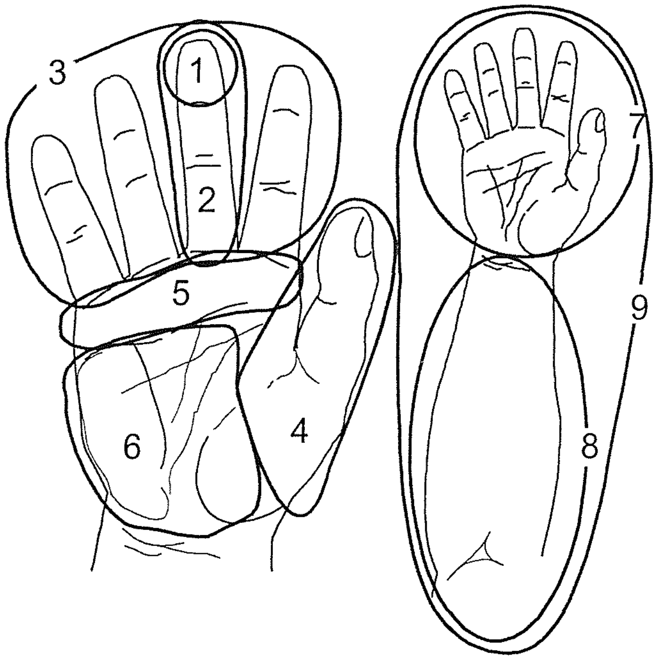


Figure 8-1 Divisions of the hand and the arm: subjects were shown the diagram and chose the number corresponding to the locations

Subjects placed their right hand, or their middle finger on the contactor. They were asked to maintain a constant contact force during the measurement either at 1 N for Conditions A and B or at 5 N for Conditions C, D and E. They were exposed to a various vibration stimulus. They were asked to indicate where they felt the sensation the most, by choosing a number corresponding to pre-defined areas displayed to the subjects (see Figure 8-1). The subjects were also encouraged to give an indication as to whether they felt the vibration on the palm side or non-palm side; they answered as 'A' for palm side and 'B' for non-palm side. For example, if the subject felt the vibration in the whole-finger on the palm side, the answer would be given as "2A".

The test was repeated with two magnitudes (i.e. 2 and 4 ms^{-2} r.m.s.), at all five frequencies, on all five contact conditions for each subject. An order of presenting stimuli was randomised for each subject.

8.4 RESULTS

8.4.1 Overall results

8.4.1.1 Effect of contact condition

In order to overview the change in the localisation of sensation due with different contact conditions, the results are presented in Figures 8-2 and 8-3 as 3-D illustrations representing the number of subjects responding with each location number (from 1 to 9) when exposed to each vibration frequency (from 8 to 125 Hz).

It is seen that contact with the fingertip (Condition A) produced sensations mainly in the finger area. With increasing contact area towards the whole hand, the location of

Stimulus intensity: 2 ms^{-2} r.m.s.

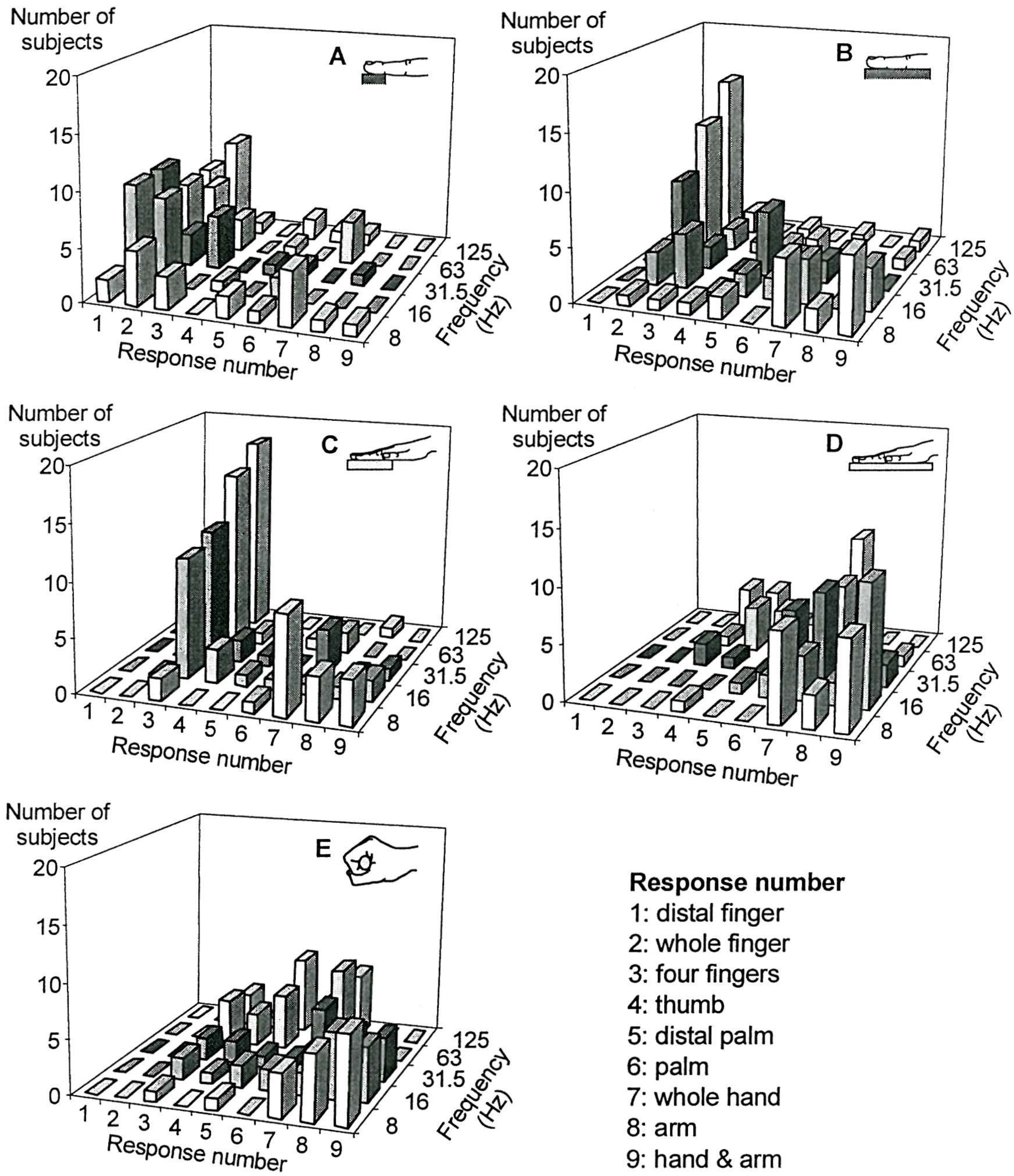


Figure 8-2 Effect of contact condition on sensation localisation. Stimulus intensity at 2 ms^{-2} r.m.s.; figures display the number of subjects (N=20) who indicated each response from 1 to 9 (see Figure 8-1) when exposed to vibration frequencies from 8 to 125 Hz.

sensation shifted to the whole area of the hand. Similar patterns of responses were obtained with hand postures D and E (i.e. pressing a plate and grasping a handle) and with the two magnitudes (i.e. 2 and 4 ms^{-2} r.m.s.).

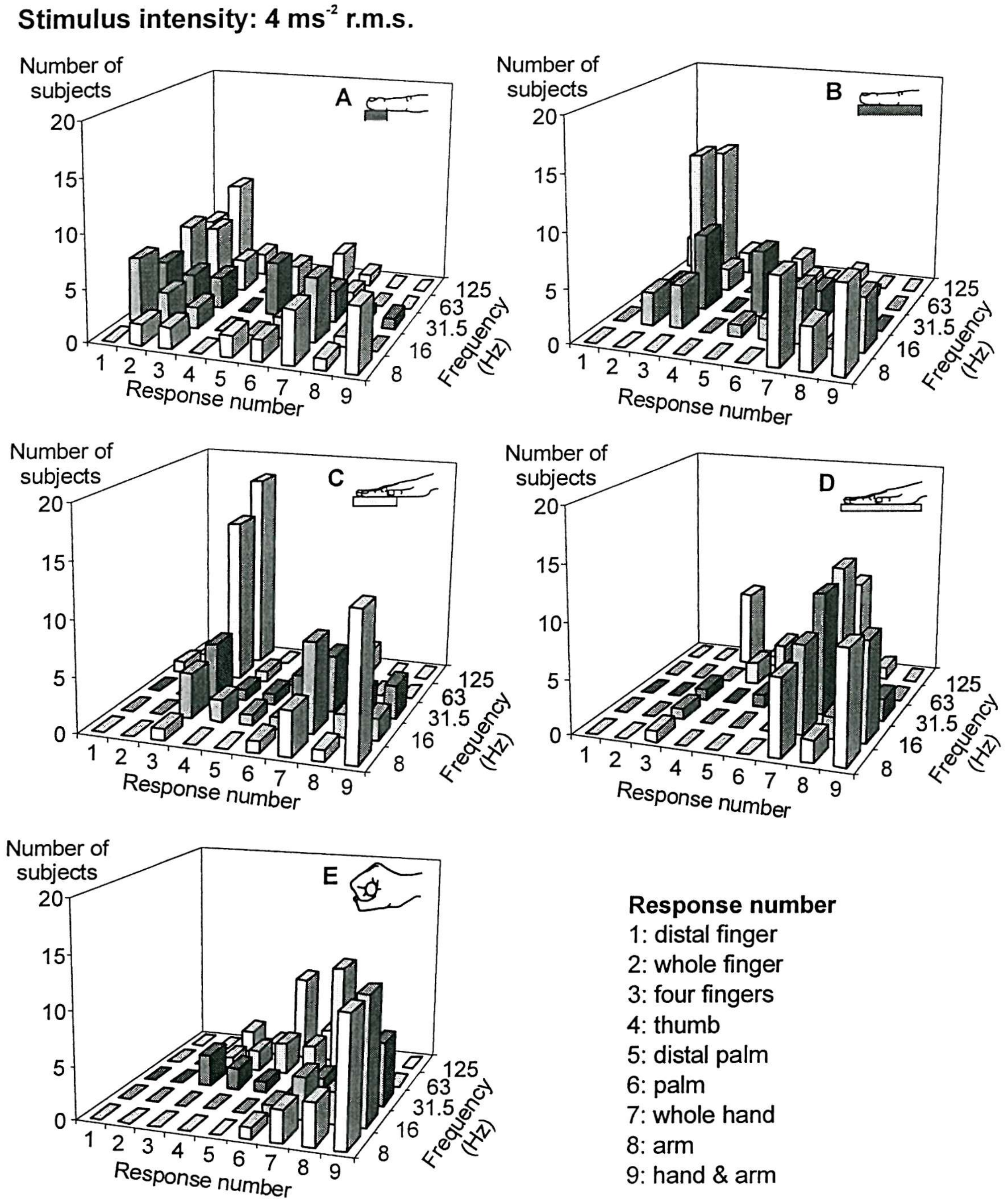


Figure 8-3 Effect of contact condition on sensation localisation. Stimulus intensity at 4 ms^{-2} r.m.s.; figures display the number of subjects (N=20) who indicated each response from 1 to 9 (see Figure 8-1) when exposed to vibration frequencies from 8 to 125 Hz.

8.4.1.2 *Effect of stimulus frequency*

The results were re-plotted by grouping the data for each stimulus frequency so as to provide a clearer presentation of the frequency effect (see Figures 8-4 and 8-5). It can be seen that vibration at 8 Hz produced sensations localised around the hand and the arm, especially with the higher intensity. With increasing stimulus frequency, the response

Stimulus intensity: 2 ms^{-2} r.m.s.

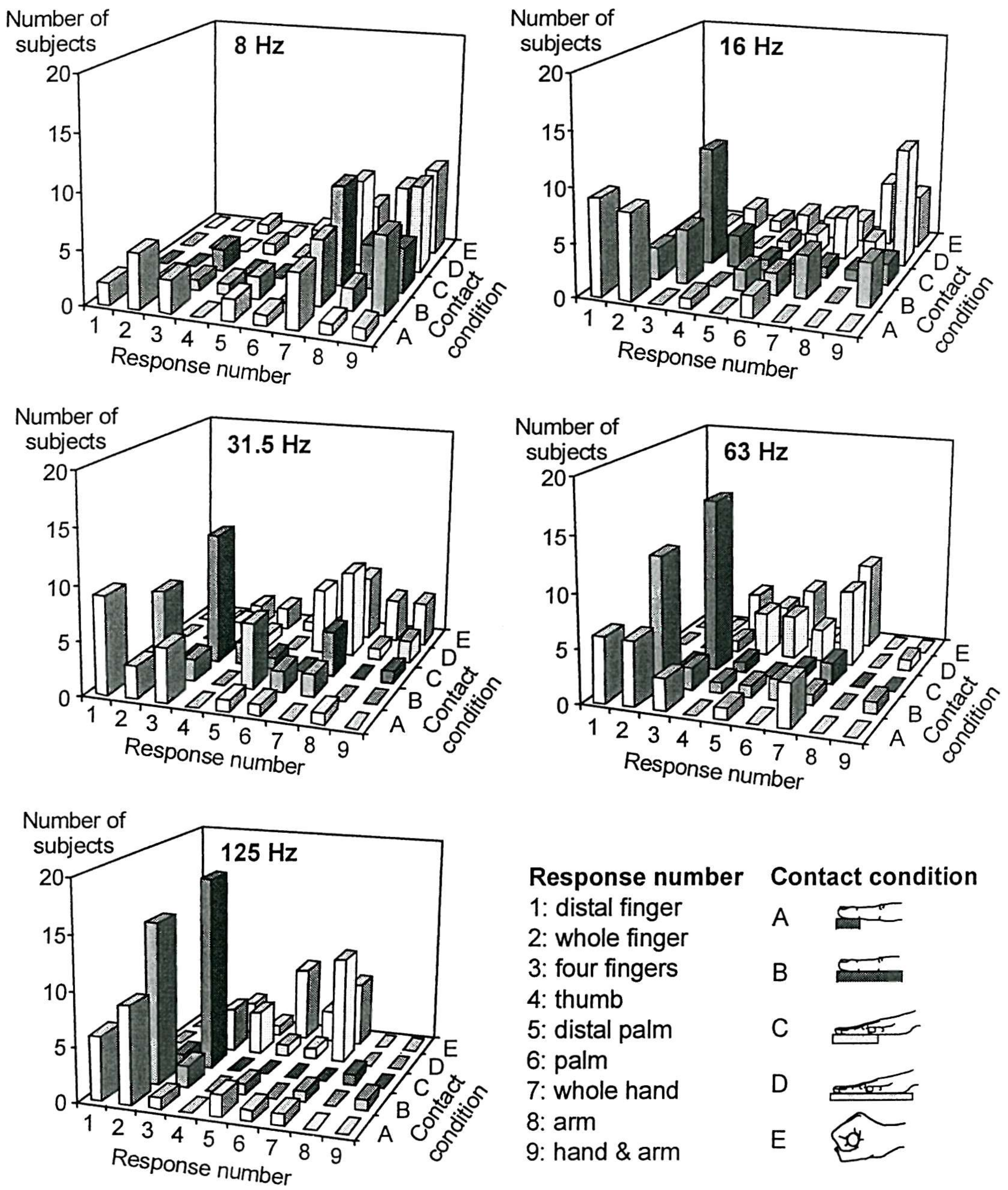


Figure 8-4 Effect of stimulus frequency on sensation localisation. Stimulus intensity at 2 ms^{-2} r.m.s.; figures display the number of subjects (N=20) who indicated each response from 1 to 9 (see Figure 8-1) when exposed to vibration with five different contact conditions.

number 3 (i.e. four fingers) was very frequently obtained with contact condition C (i.e. four fingers), with the population response increasing with increasing frequency up to 125 Hz. It therefore seems that the localisation of sensation produced by hand-transmitted vibration depend on vibration frequency as well as contact area.

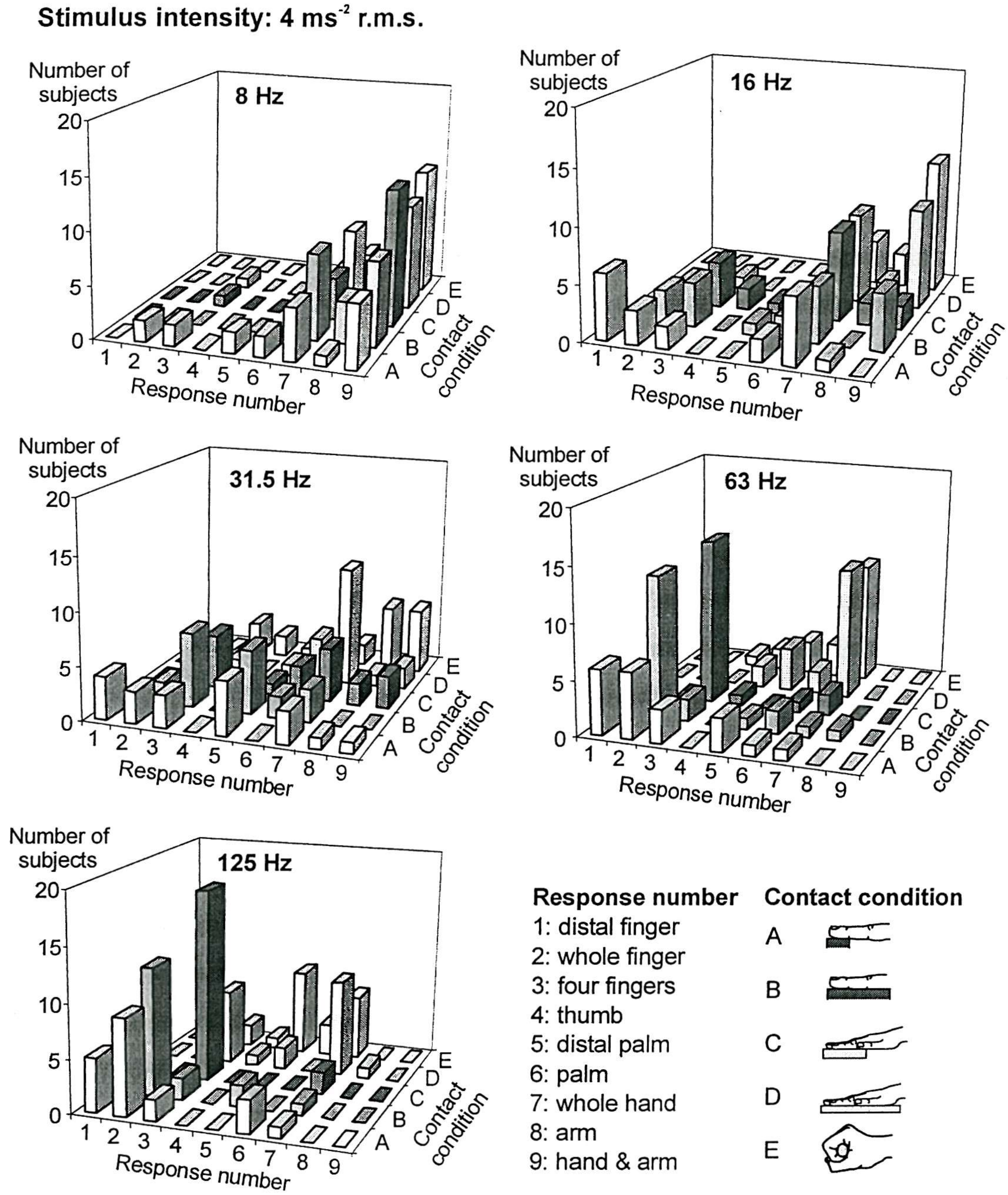


Figure 8-5 Effect of stimulus frequency on sensation localisation. Stimulus intensity at 4 ms^{-2} r.m.s.; figures display the number of subjects (N=20) who indicated each response from 1 to 9 (see Figure 8-1) when exposed to vibration with five different contact conditions.

8.4.1.3 *Effect of stimulus intensity*

There seems to be little effect of changes in stimulus intensity from 2 to 4 ms^{-2} r.m.s. However, exposure to the higher intensity may enhance the effects of contact condition and frequency, as shown throughout Figures 8-2 to 8-5.

8.4.2 Statistical analysis

The results shown above suggest a couple of trends which seem consistent with the hypothesis stated in Section 8-1: i) a dependence on contact condition, in which the localisation of sensation tends to correspond to the section of the hand in contact with the vibrating surface, ii) a dependence on stimulus frequency, in which the localisation of sensation tends to be directed towards the arm area with lower frequencies of vibration (i.e. 8 and 16 Hz) and to be localised nearer the contact location with higher frequencies of vibration (i.e. 63 and 125 Hz).

In order to test whether the data support the hypothesis, it was necessary to perform statistical tests. The location numbers given by subjects (i.e. 1 to 9) were treated as related samples and are nominal values, rather than ordinal values. Nonparametric statistical tests, Cochran Q test for the k-sample case and the McNemar test for the two-sample tests were applicable to the design of the experiment. However, these tests are suited for use with related samples of dichotomous nominal data. Therefore, the responses given by the subjects (i.e. 1 to 9) were modified to dichotomous values (i.e. 1 and 0) according to the following procedure: any responses indicating that subjects felt the vibration stimulus within the contact location were included in '1'; any responses indicating that the subjects felt the vibration stimulus in an area other than at the contact location were identified as '0'. Table 8-3 shows a systematic process for determining dichotomous values. For instance, if a response of 1 (i.e. distal finger) were obtained with the contact condition B (i.e. whole finger), the modified response was '1', whereas if a response of 5 (i.e. proximal palm) were obtained with the same contact condition B, the modified response was '0'.

Table 8-3 Systematic modified response categorisation. A category of '1' indicates subjects felt the vibration at the contact location being applied. A category of '0' indicates that the subjects felt the vibration at any location other than at the contact location.

Contact condition	Modified response	
	1	0
	Response from subjects	
A	1	2,3,4,5,6,7,8,9
B	1,2	3,4,5,6,7,8,9
C	1,2,3	4,5,6,7,8,9
D	1,2,3,4,5,6,7	8,9
E	1,2,3,4,5,6,7	8,9

8.4.2.1 Effect of contact condition

The modified results were grouped within individual contact conditions and are presented in Figure 8-6. According to the overall analysis using the Cochran Q test, the results were influenced by the contact conditions at all frequencies (Cochran Q, $p<0.01$), with the exception of 16 Hz (Cochran Q, $p=0.79$ for 2 ms^{-2} r.m.s., $p=0.157$ for 4 ms^{-2} r.m.s.).

With increasing contact area, from the fingertip to the whole hand (i.e. Conditions A and B), the response pattern was the same for all frequencies (McNemar, $p>0.05$), with the exception of 125 Hz where there was a significant change in response from '0' to '1' (McNemar, $p=0.02$ at 2 ms^{-2} r.m.s., $p=0.002$ at 4 ms^{-2}),. No changes in response were obtained with increasing contact area from the whole finger to the four fingers (i.e. Conditions B to C) (McNemar, $p>0.2$), except for 16 Hz at 2ms^{-2} r.m.s. (McNemar, $p=0.02$).

As the area of contact with the vibrating surface increased from the four fingers to the whole hand (i.e. Conditions C to D), it is seen that the subjects were more likely to respond with '1' and were unchanged between the Conditions C and D. This trend seems evident for the lower magnitude of vibration (McNemar, $p>0.1$), except for 8 Hz where there was a change of response from '0' to '1' (McNemar, $p=0.016$),. With the higher stimulus intensity at 4 ms^{-2} r.m.s., there was a change of response from '0' to '1' when exposed vibration at 8 and 31,5 Hz (McNemar, $p<0.01$).

The responses were not different between the two hand postures (i.e. D and E) at any frequency (McNemar, $p>0.1$), except for 31.5 Hz at 4 ms^{-2} r.m.s. (McNemar, $p=0.004$).

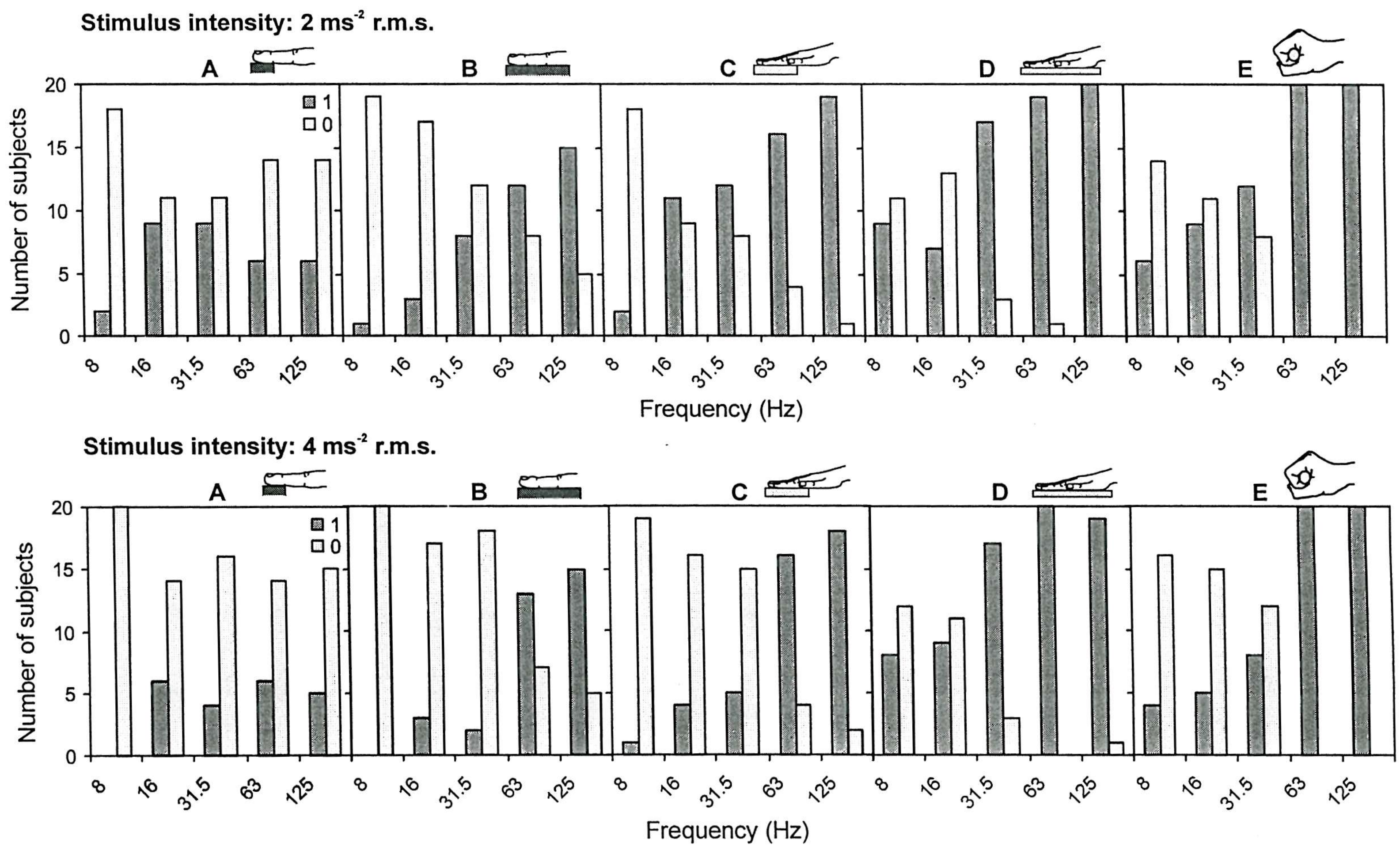


Figure 8-6 Dichotomous responses (i.e. 0 and 1) from subjects obtained by the procedure in Table 8-3. A category of '0' indicates that subjects felt the vibration at any location other than at the contact location. N=20.

8.4.2.2 Effect of stimulus frequency

The results are re-plotted with a different presentation in Figure 8-7, showing the percentage of subjects whose response corresponds to either '1' or '0', grouped by frequency.

When exposed to vibration at a lower frequency, the responses from subjects were generally '0', whereas when exposed to vibration at a higher frequency, the responses were mostly '1', this trend was statistically significant for all contact conditions (Cochran Q, $p<0.001$), except for Condition A (Cochran Q, $p=0.088$).

With an increase in stimulus frequency from 8 to 16 Hz, the responses were almost unchanged (McNemar, $p>0.25$), except with Condition A (McNemar, $p=0.016$ for 2 ms^{-2}, $p=0.031$ for 4 ms^{-2}) and Condition C (McNemar, $p=0.004$ for 2ms^{-2}).

A significant change in response was obtained only with Condition D when changing the stimulus frequency from 16 to 31.5 Hz (McNemar, $p=0.006$ for 2 ms^{-2}, $p=0.008$ for 4 ms^{-2}).

No difference in response was obtained between the two higher frequencies (i.e. 63 and 125 Hz) for any contact condition (McNemar, $p>0.3$).

When comparing the results obtained with low and high frequency stimuli, the response of '0' were altered to '1', and vice-versa. The trend was significant with the pairing of frequencies at 8 and 63 Hz, 8 and 125 Hz, 16 and 63 Hz, and 16 and 125 Hz (McNemar, $p<0.01$), except for Condition A (McNemar, $p>0.05$).

8.4.2.3 Effect of hand posture

Although statistical tests did not show significant differences in response between Condition D (flat hand posture) and Condition E (handle gripping posture) (McNemar, $p>0,1$), the response pattern for the two conditions seemed slightly different. A careful observation of Figures 8-2 and 8-3 shows that Condition D produced sensations mainly around the area of the whole hand (number 7), whereas Condition E produced sensations mostly around the fingers (number 4) and distal part of palm (number 5).

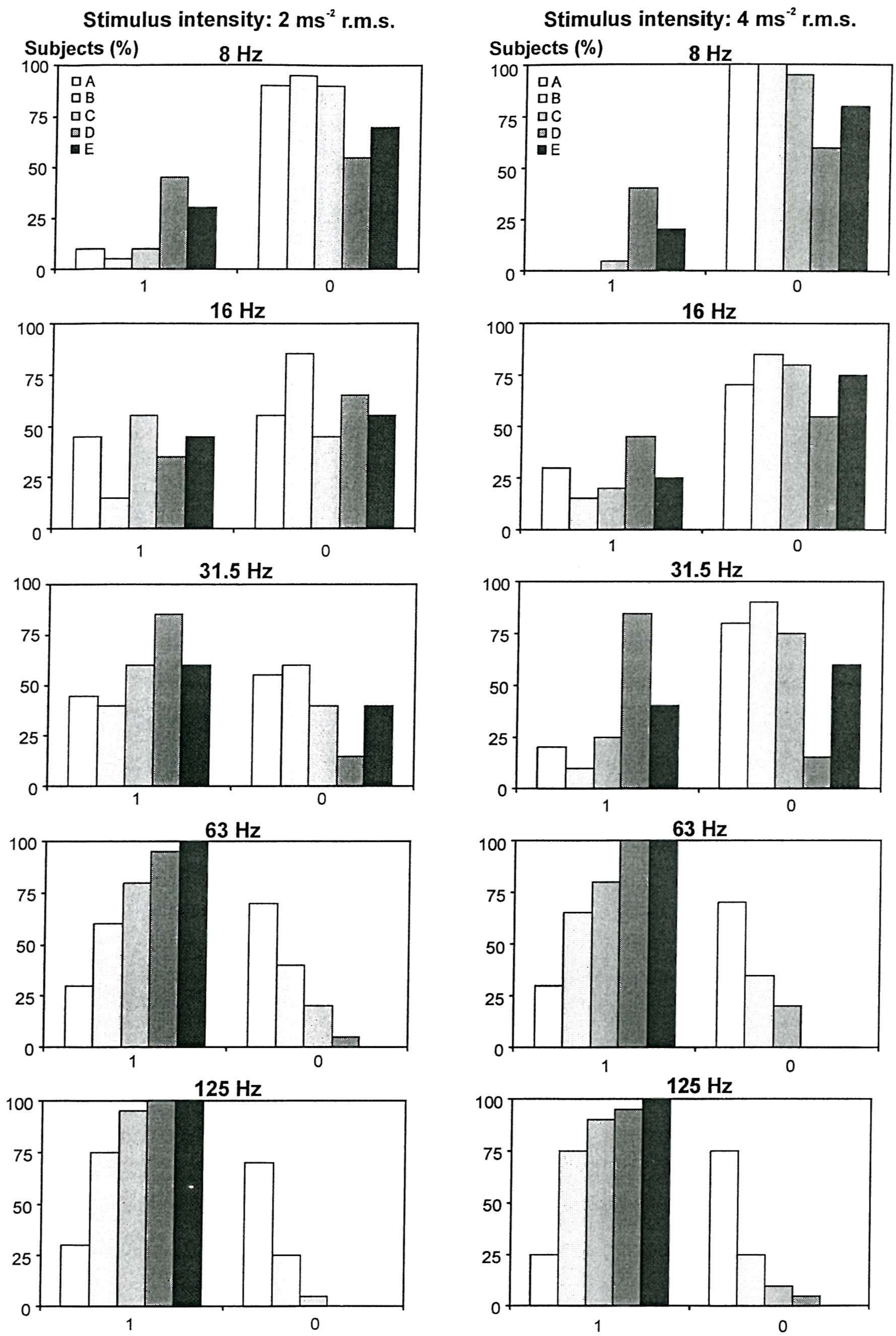


Figure 8-7 Dichotomous responses (i.e. 0 and 1) from subjects, grouped by stimulus frequency.

8.4.2.4 *Effect of stimulus intensity*

As may be expected from Figures 8-6 and 8-7, the statistical analysis showed no significant difference in response between the two magnitudes (2ms^{-2} and 4 ms^{-2}) (McNemar, p>0.05), apart from one comparison: Condition C at 31.5 Hz (McNemar, p=0.039).

8.5 DISCUSSION

The results indicate that both contact area and stimulus frequency contributed to altering the localisation of the area of sensation caused by hand-transmitted vibration. This may be partly explained by the dynamic responses of the hand-arm system.

The human hand-arm system has resonance frequencies, which are individual and depend on several factors (e.g. vibration direction, grip force, muscle tension, position of arm) that vary the transmission of vibration energy to different parts of the hand and the arm to various degrees (Lundström, 1984b). Several studies have reported a frequency dependence in the transmission of vibration: vibration at frequencies above 100 Hz tend to be isolated to the areas of the hand and fingers directly in contact with the vibrating surface, while at frequencies below 100 Hz much of the vibration directed into the fingers is transmitted to the hand (e.g. Reynolds and Jokel, 1974; Reynolds and Angevine, 1977; Sörensson and Burström, 1997). It seems that the localisation of sensation reflects where the vibration is transmitted.

The results indicate that the sensations were directed towards the wrist and arm area with decreasing frequency, whereas the sensation tended to remain at the area in contact with the vibrating surface with increasing frequency. A reasonable explanation is that amplification of vibration transmitted to a particular area of the hand results in the excitation of a larger number of receptors in the vicinity of the area. The more vibration energy is transmitted, the larger the population of receptors activated. In addition, for the lowest frequency (i.e. 8 Hz), a larger displacement was generated (4.5 mm (peak-peak) for 2 ms^{-2} r.m.s. and 9.0 mm (peak-peak) for 4 ms^{-2} r.m.s.) it is possible that large relative motions between tissues in the hand and across joints caused easier detection of motions.

There seemed to be a postural effect on the localisation of sensation, particularly with high frequencies around 100 Hz. The responses were more scattered around the fingers and the knuckle area when applied with a handle gripping posture, but more around the whole hand area when applied with a flat palm. There has been little study of the effect of hand posture on hand-transmitted vibration, only a series of studies conducted by Reynolds and co-authors investigating biodynamic and subjective responses employing a 'finger grip' (grasping a handle using only the fingers) and a 'palm grip' (grasping a handle with the fleshy part of the palm). They found no obvious difference in response between the two postures, apart from greater energy directed into the hand with the palm grip than for the finger grip.

A similarity was observed between the transmission results of the other studies and the current localisation of sensation with a handle grasping posture. Reynolds and Angevine (1977) measured transmissibility by attaching a piezo-resistive accelerometer to seven different locations on the hand and arm with exposure to hand-transmitted vibration in frequency range 5 to 100 Hz using a handle grasping posture ('finger grip' and 'palm grip). The findings indicated that vibration up to around 100 Hz was directed with little attenuation from the point of contact between the finger and the vibrating handle through the finger to the back surface of the finger. The transmissibility increased at the knuckle location around 100 Hz. This was also seen in a similar study by Sörensson and Lundström (1992). They measured the transmission of vibration from a vibrating handle at twelve different locations in the hand-arm system by using a laser velocity transducer so as to achieve measurement without contact with the skin. One of the findings in the results was an amplification of vibration by about 7 dB at 80 Hz seen at a particular location on the hand (i.e. the proximal phalanx of the middle finger). This suggests that the vibration from a handle may transmit to a particular area of the hand proximal to the fingers and distal to the palm, causing the excitation of receptors around the area and making detection of vibration easy, even when the whole area of the hand is in contact with the vibrating surface. Another possible explanation for the effect of hand posture on subjective response would be due to the varying pressure at the particular location in the hand: a smaller area when pressing downwards on a handle results in a higher pressure than when pressing with the same force on a flat plate.

The current study found no change in the location of areas of sensation due to changes in vibration magnitude from 2 to 4 ms^{-2} r.m.s. Both stimulus magnitudes used in the study were well above threshold over the frequency range (i.e. 8 to 125 Hz). Different results may be obtained with magnitudes near to threshold level, or far higher than the threshold level, as it is possible that the amount of transmission could alter due to the change of vibration magnitudes.

8.6 CONCLUSIONS

The localisations of the sensations produced by hand-transmitted vibration were greatly influenced by contact area and stimulus frequency, partly due to the mechanical characteristics of the hand system.

1. When exposed to high frequency stimuli, above about 63 Hz, the sensations tended to be localised at the point of contact between the glabrous skin of the hand and the vibrating surface.
2. When exposed to low frequency stimuli, below about 31.5 Hz, the sensations tended to be directed towards the proximal area of the hand and to the arm.
3. The above two effects were stronger with larger contact areas.
4. There was little change in the localisation of sensation between two different magnitudes of vibration (at 2 and 4 ms^{-2} r.m.s.)
5. Hand posture (a flat palm pressing posture and a hand grasping posture) influenced the sensation localisation: sensations became concentrated around the proximal part of fingers and the knuckle when applying a handle gripping posture.

CHAPTER 9

STUDY 6 SENSATION MAGNITUDE: EFFECT OF STIMULUS FREQUENCY AND CONTACT AREA

9.1 INTRODUCTION

A series of laboratory experiments conducted by the author on absolute thresholds (see Chapters 4 to 7) showed evidence of spatial summation of absolute thresholds for hand-transmitted vibration: there was an increase in detection sensitivity with increasing contact area. It is not known whether a change of contact area at the glabrous skin of the hand can also influence the detection sensitivity at supra-threshold levels. There are psychophysical methods for determining perception strength at supra-threshold levels. According to the spatial summation effect, a greater sensitivity should be observed with increasing area of contact with a vibrating surface.

Investigations of the sensation magnitude of vibration stimuli have been undertaken in order to determine the growth of sensation as a function of intensity at a number of different frequencies, and also to establish contours of equal subjective intensity. Frequency contours of equal subjective magnitude are a common method of presenting such results and have been established for the fingertip (Stevens 1959, 1968), for the thenar eminence (Verrillo, *et al.*, 1969; Verrillo, 1970) and for the whole hand (Miwa, 1967; Reynolds, 1977; Maeda and Iwata, 1983). There is evidence to suggest that the exponent of the psychophysical function for vibration depends on stimulus frequency, and it has been found that there is a decrease of the exponent (in Steven's power law) with increasing stimulus frequency (see Stevens, 1968).

It was expected by the present author that the subjective magnitude of vibration would depend on not only stimulus variables but also on other variables. A hypothesis provided for the study was, referring from the spatial summation effect, greater sensation magnitude should be observed with increasing areas of contact with a vibrating surface. An experiment was conducted to investigate greatness of sensation caused by hand-transmitted vibration depends on contact area as well as stimulus frequency.

9.2 OBJECTIVES

In this study, sensation magnitudes were determined using the method of magnitude estimation introduced by Stevens (see Stevens, 1975). Sensation magnitudes for hand-transmitted vibration were compared between stimulus frequencies from 8 to 125 Hz, with changes in contact area and changing hand postures.

Two separate tests were performed: one (called a 'frequency comparison test') examined the effect of frequency, and the other (called a 'contact comparison test') examined the effect of contact area on subjective greatness. Both tests were performed with two different stimulus magnitudes to investigate whether equal sensation contours are affected by stimulus magnitude.

9.3 METHOD

9.3.1 Subjects

Twenty male students, aged between 18 and 25 years (mean 20.4 years), served as subjects. They also participated in the previous experiment (Study 5). The characteristics of their bodies, hands and fingers are summarised in Table 8-1.

9.3.2 Stimuli and contact conditions

Sinusoidal vibration at frequencies of 8, 16, 31.5, 63 and 125 Hz, each 2.0 seconds in duration were created as test stimuli. Each stimulus was tested with two different magnitudes: at 2 and 4 ms^{-2} r.m.s.

Five different contact conditions were prepared: exactly the same conditions employed in the previous study (see Table 8-1 for illustrations and details):

Condition A	Middle fingertip
Condition B	Whole middle finger
Condition C	Four fingers
Condition D	Whole hand (flat plate pressing posture)
Condition E	Whole hand (handle grasping posture)

For each condition, the contact force on the vibrating surface was controlled (1N for Condition A and B, 5N for Condition C, D and E).

A pair of ear defenders was provided for subjects in order to prevent them perceiving vibration stimuli by hearing, although most of the stimuli were inaudible to the subjects.

The skin temperatures of the subject's fingertips (middle finger) were measured at the beginning of every session, and the measurement only proceeded if the skin temperature was higher than 29 °Celsius.

9.3.3 Procedure

9.3.3.1 Frequency comparison test

The 'frequency comparison test' was performed to determine equal sensation contours for each contact condition.

Subjects placed their fingers or hand according to the contact condition being studied.

The subjects were exposed to a set of two stimuli: the first stimulus was a 2.0 second reference stimulus fixed at the mid-range frequency (i.e. 31.5 Hz), the second stimulus was a test stimulus at one of the five frequencies (i.e. 8, 16, 31.5, 63 or 125 Hz). Both stimuli were at the same magnitude, either at 2.0 or 4.0 ms^{-2} r.m.s. There was a pause of one second between the two stimuli.

The subjects were told that the reference stimulus had a sensation magnitude given by a fixed number, '100'. The task of the subjects was to compare the greatness of the two stimuli and give a number for the test stimulus relative to the reference stimulus. For instance, if the subjective greatness of the test stimulus was twice as great as the reference stimulus, the subject should give the number '200'. If the subjective greatness of the test stimulus was half the greatness of the reference stimulus, the subject should give the number '50'.

The test was repeated with two magnitudes (i.e. 2 and 4 ms^{-2} r.m.s.) with all five contact conditions for each subject.

9.3.3.2 'Contact comparison test'

Another test, the 'contact comparison test', was carried out to investigate changes of sensation magnitude due to a change of contact area.

A pair of 31.5 Hz stimuli, each lasting two seconds was used. The first stimulus was the reference stimulus and the second was the test stimulus.

The subjects were asked to place their hand so that the whole middle finger was exposed to the reference stimulus. They were then asked to change the contact condition as indicated by the experimenter before receiving the test stimulus. Due to the difficulty of swapping a handle quickly with a flat table, Condition E (handle grasping posture) was not included in the test.

The subjects were told that the sensation magnitude of the reference stimulus represented "100". Their task was to reply with a number that represented greatness of the sensation perceived with the second stimulus, relative to the reference. The test was repeated with two magnitudes (i.e. 2 and 4 ms^{-2} r.m.s.) for each subject.

In order to make the subjects familiar with the procedure and the vibration stimuli, a practice session was presented to each subject prior to the main tests.

9.3.4 Vibration measurement and analysis

The vibration stimuli generated at the contactor source were measured during each test, which was achieved by attaching a piezoelectric accelerometer (DJ Birchall, type A/20T) beneath the contactor surface (i.e. the flat plate or the handle). This was to determine whether the vibration stimuli were generated at the desired magnitude over the tests. The measured acceleration of both the reference and the test stimuli for all measurement conditions are displayed in Appendix D6-1 to D6-4 for the 'frequency comparison test' and Appendix D6-9 to D6-10 for the 'contact comparison test'. It is seen that the acceleration values varied between measurement conditions and, to a greater extent, between subjects.

The coefficient of variation in vibration magnitudes over subjects (i.e. standard deviation divided by the mean acceleration of the 20 subjects) was calculated for each condition and found mostly to be less than 10%, although higher values were obtained at higher frequencies, especially at 125 Hz (up to 15%). It was thought that magnitudes differing from the desired magnitude (i.e. 2 or 4 ms^{-2} r.m.s.) would not affect results as long as the reference and the test stimuli were at the similar intensity. In order to investigate this, the ratio of the reference and test magnitudes were calculated (see Appendix D6-5 to D6-6 and Appendix D6-11) and were found to be close to 1.0 for all test conditions. The coefficient of variation for the ratio of two stimuli was generally less than 10%, except for the 125 Hz test stimulus at 2 ms^{-2} r.m.s.

This experiment was not designed to investigate components of growth of sensation with change of magnitude but the effect on sensation of frequency and contact area. Although there was some variance in the generated acceleration magnitudes between subjects and test conditions, all analysis was carried out on the assumption that the vibration magnitudes expressed by the subjects were either 2 or 4 ms^{-2} r.m.s.

9.4 RESULTS

9.4.1 'Frequency comparison test'

9.4.1.1 Effect of stimulus frequency

Figures 9-1 and 9-2 show the individual judgements of sensation magnitude for all five contact conditions obtained at two different magnitudes (2 and 4 ms^{-2} r.m.s.). It is seen that the sensation magnitudes varied from 20 to 500, showing frequency dependence for each contact condition: an increase of sensation magnitude with decreasing stimulus frequency from 125 to 8 Hz. A higher value of sensation magnitude represents the subject feeling the test frequency stronger compared to the reference frequency when they are at the same magnitude of acceleration. This is opposite to perception thresholds (a higher threshold represents less sensitivity).

Taking a look at the responses obtained with the test frequency of 31.5 Hz, which is the same frequency as the reference stimulus, almost all the subjects gave responses close to '100'. This suggests that the subjects made their subjective judgements by comparing sensations caused by the two stimuli without being affected by the presentation order.

In each graph in Figures 9-1 and 9-2, it can be generally observed that there are higher sensation magnitudes at lower frequencies (i.e. 8 and 16 Hz), whereas lower values at higher frequencies (i.e. 63 and 125 Hz). This trend is less strong with larger contact areas, where there is a lower sensation magnitude at low frequencies.

Stimulus intensity: 2 ms^{-2} r.m.s.

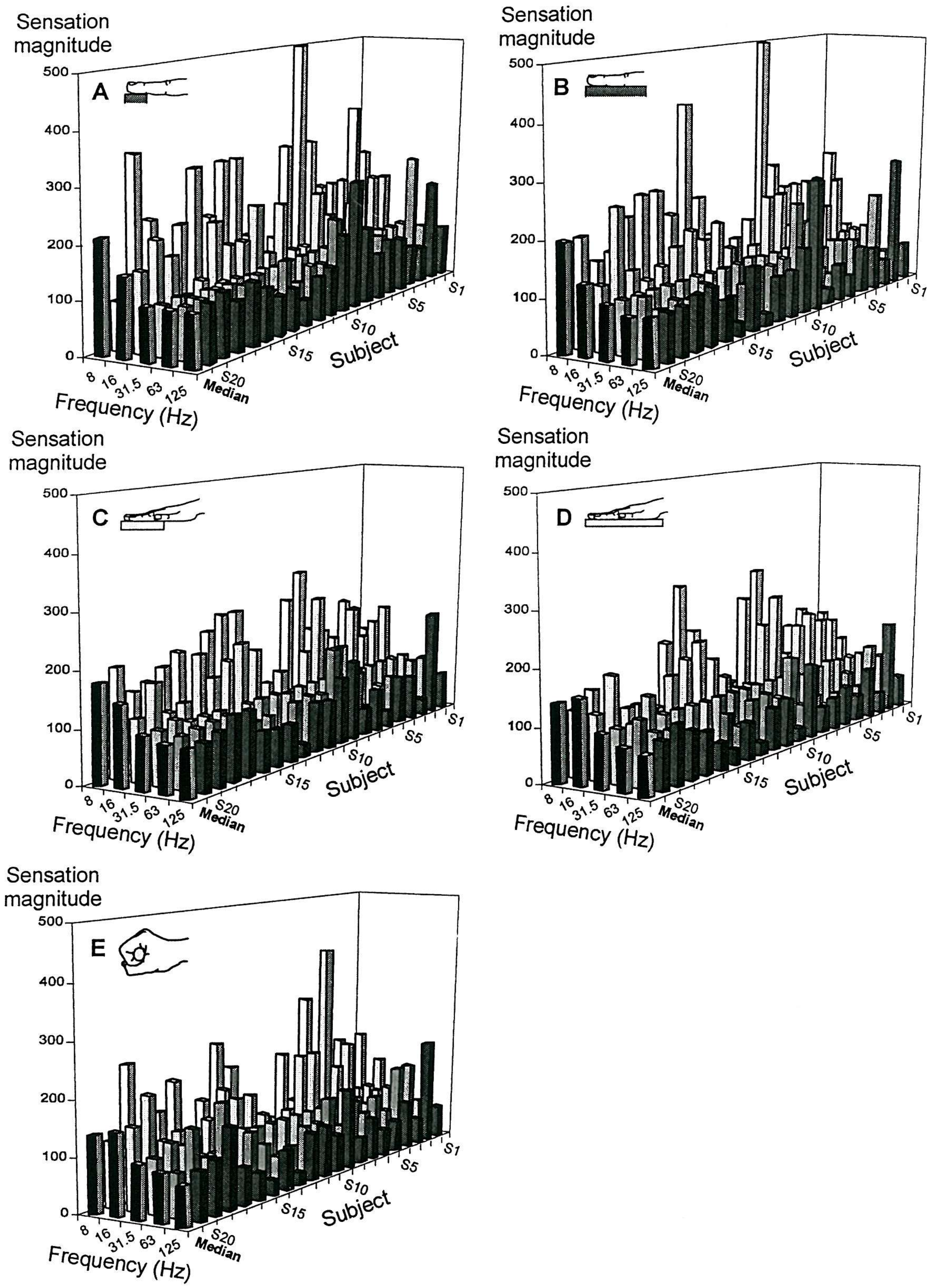


Figure 9-1 Individual judgements of sensation magnitude for 20 subjects when exposed to 2 ms^{-2} r.m.s. at five stimulus frequencies (from 8 to 125 Hz), with five contact conditions. (Reference stimuli at 31.5 Hz, 2ms^{-2} r.m.s.)

Stimulus intensity: 4 ms^{-2} r.m.s.

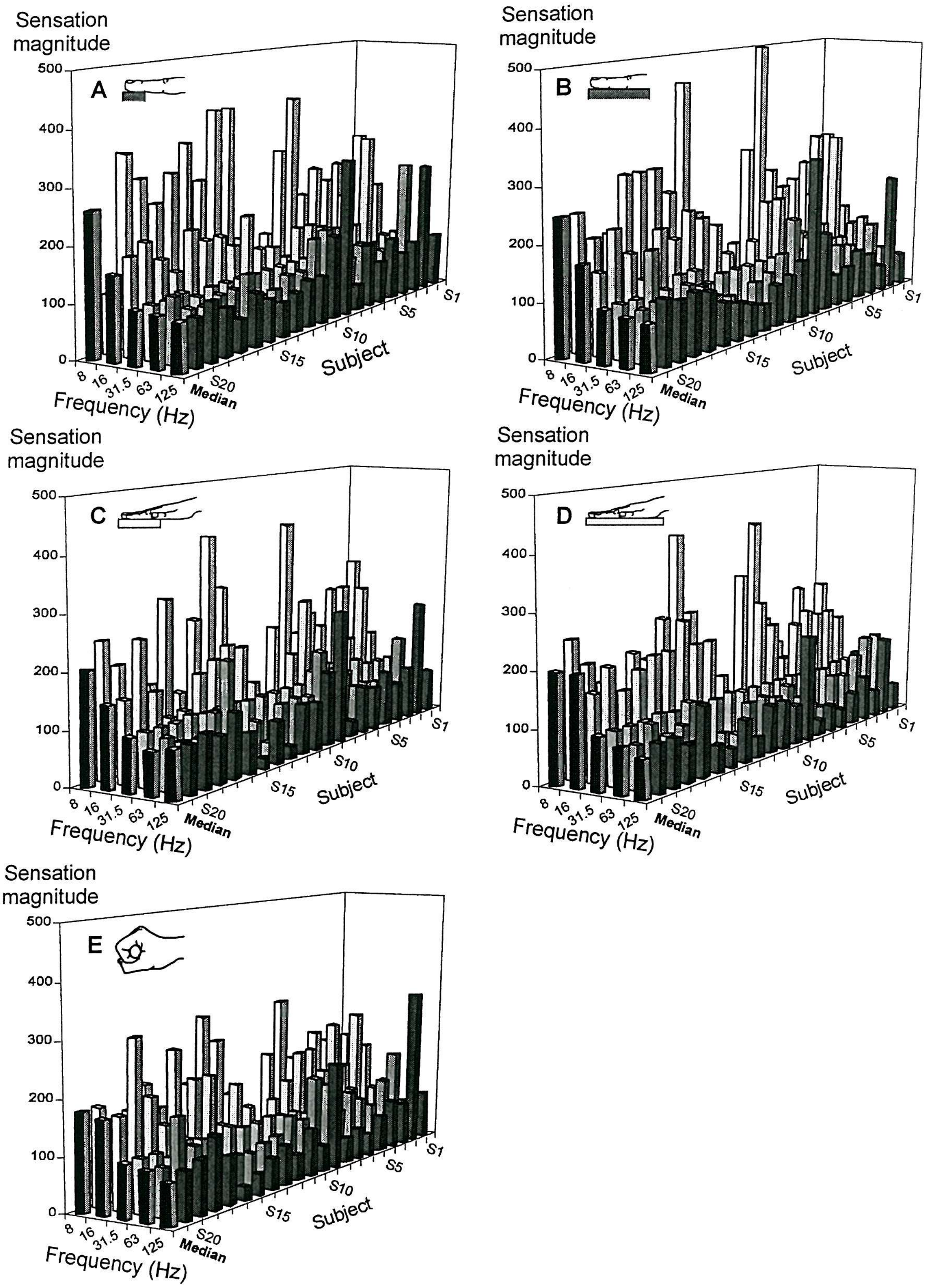


Figure 9-2 Individual judgements of sensation magnitude for 20 subjects when exposed to 4 ms^{-2} r.m.s. at five stimulus frequencies (from 8 to 125 Hz), with five contact conditions. (Reference stimuli at 31.5 Hz, 4 ms^{-2} r.m.s.)

Figure 9-3 displays equivalent sensation contours for five contact conditions, determined by taking median values of judgements from twenty subjects for each contact condition at each of two different stimulus intensities. The *lines connecting points* indicate subjective greatness when exposed to the various stimulus frequencies (from 8 to 125 Hz) with constant vibration magnitude.

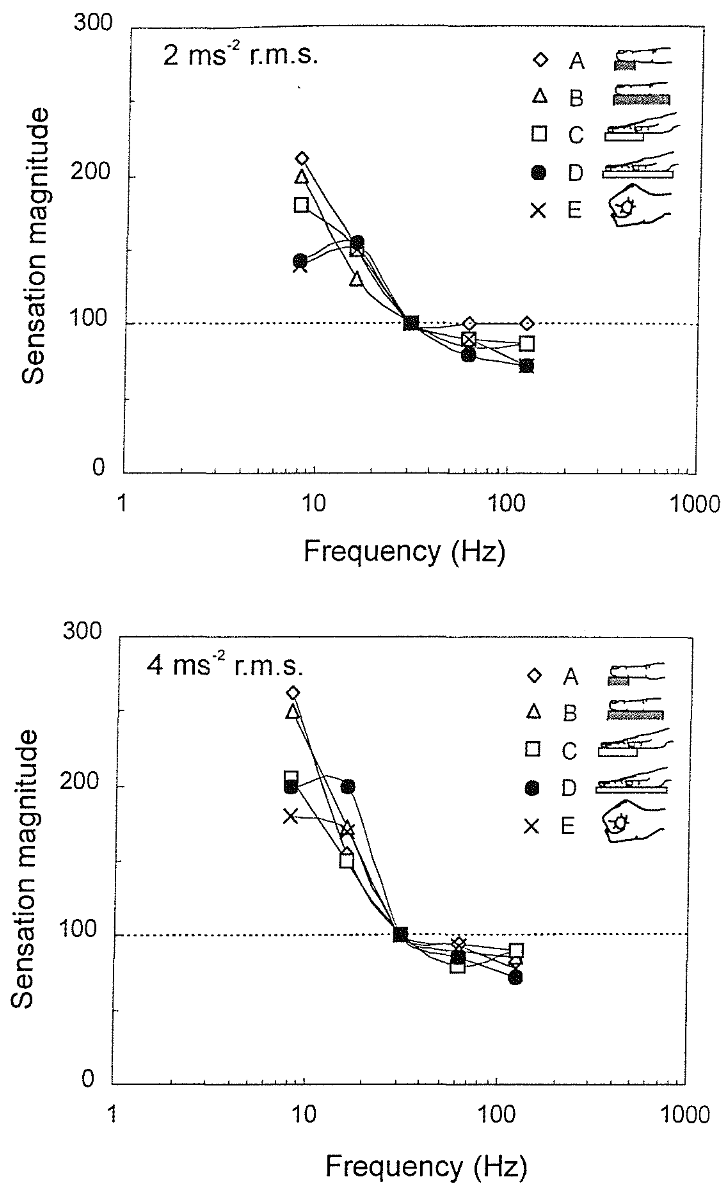


Figure 9-3 Sensation magnitudes for obtained by five different contact conditions. The sensation levels refer to 31.5 Hz. Medians of 20 subjects are shown separately for 2 and 4 ms^{-2} r.m.s.

Statistical analysis indicated a significant frequency dependence of sensation magnitude for all five contact conditions (Friedman, *p*<0.01). As can be seen in Figure 9-3, the sensation magnitudes increased with decreasing test frequency below 31.5 Hz, which was significant for the conditions with smaller contact area (i.e. Conditions A, B and C, Wilcoxon, *p*<0.01). For the larger contact areas causing vibration of the whole hand (i.e. Condition D and E), the sensation magnitude was unchanged between at 8 and 16 Hz (Wilcoxon, *p*>0.5).

With increasing test frequency above 31.5 Hz, some conditions displayed a decreased sensation magnitude, and some showed no change in greatness. Between 63 and 125 Hz, the sensation magnitude seemed unaffected by a change of test frequency with any contact condition (Wilcoxon, $p>0.1$), except for Conditions B and C with the stimulus intensity at 4 ms^{-2} r.m.s. (Wilcoxon, $p<0.05$).

9.4.1.2 Comparison between two different intensities

The median results of twenty subjects for all test conditions were then re-plotted into a single graph, as seen in Figure 9-4, so as to allow a comparison of the results obtained between two different magnitudes. According to a visual judgement from Figure 9-4, relative to 31.5 Hz, the sensation magnitude at the lower two test frequencies (i.e. 8 and 16 Hz) was greater with the 4 ms^{-2} r.m.s. stimulus. This was statistically significant with Conditions B, C and D (Wilcoxon, $p<0.05$).

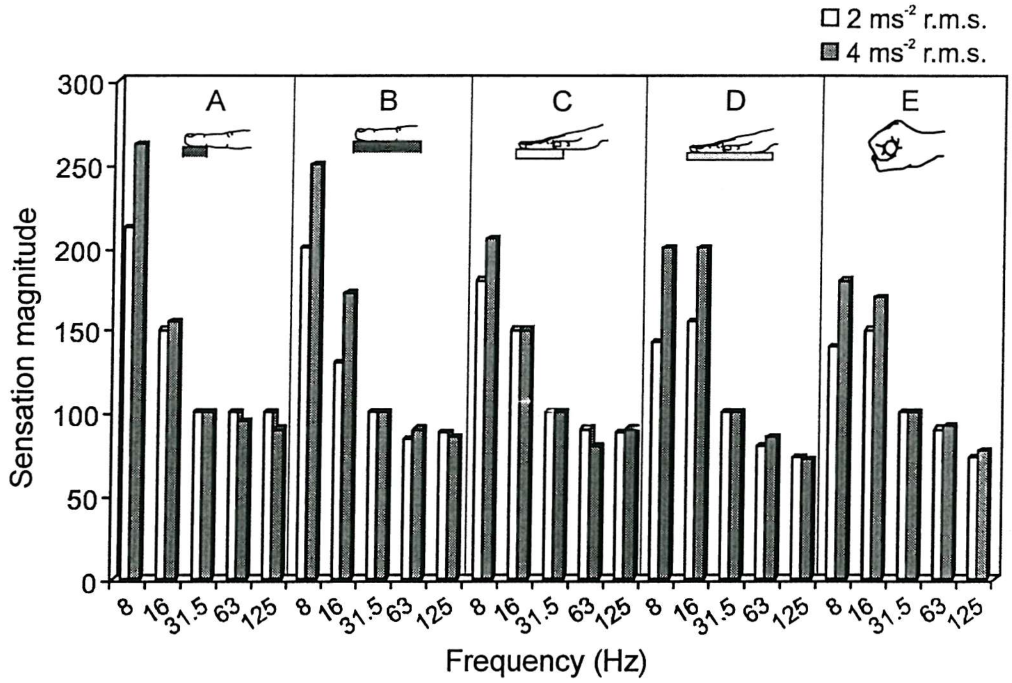


Figure 9-4 Comparison of sensation magnitudes obtained between two magnitudes (i.e. 2 and 4 ms^{-2} r.m.s.). Reference stimulus at 31.5 Hz.

9.4.2 'Contact comparison test'

9.4.2.1 *Effect of contact area*

It seems that changes of the area of contact with a vibrating surface can also change sensation magnitude. Figure 9-5 shows individual responses for four contact conditions when exposed to 31.5 Hz vibration at 2 and 4 ms^{-2} r.m.s.

The effect of contact area seems to exist with both stimulus magnitudes, indicating that an increase in contact area provided greater sensation (Wilcoxon, $p<0.05$).

A few subjects provided sensation magnitude values of '250' with whole hand contact (i.e. Condition D) when exposed to 4 ms^{-2} r.m.s. This means the subjects sometimes felt the vibration to be more than twice as great with the whole hand as with the whole middle finger.

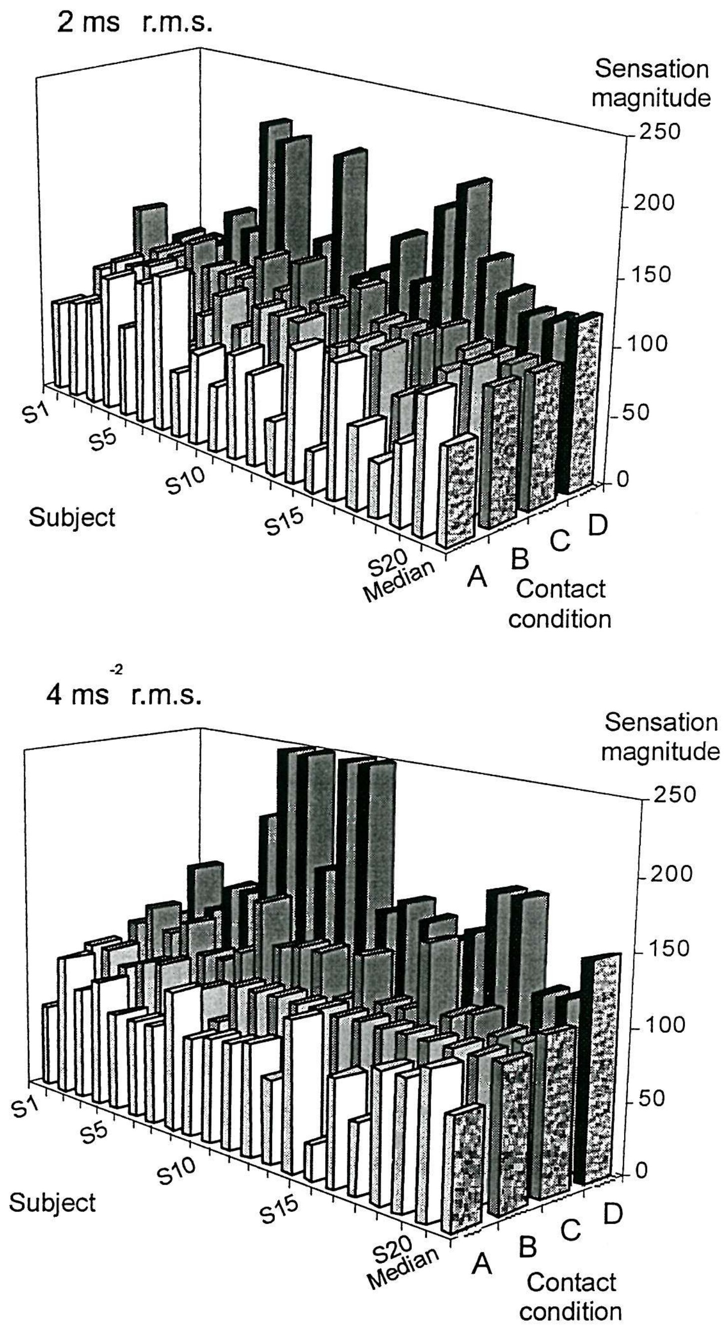


Figure 9-5 Individual sensation magnitudes provided by 20 subjects exposed to 31.5 Hz at 2 and 4 ms^{-2} r.m.s. compared to a reference contact with Condition B (whole middle finger contact).

9.4.2.2 *Comparison between two different intensities*

Figure 9-6 shows median sensation magnitudes for the twenty subjects, comparing the dependence in area at two stimulus intensities. It is clear that subjective greatness systematically increased with increasing contact area from the fingertip to the whole hand at both stimulus intensities. A significant difference in response was obtained between the two magnitudes with the larger contact areas, Condition C and D (Wilcoxon, *p*<0.05).

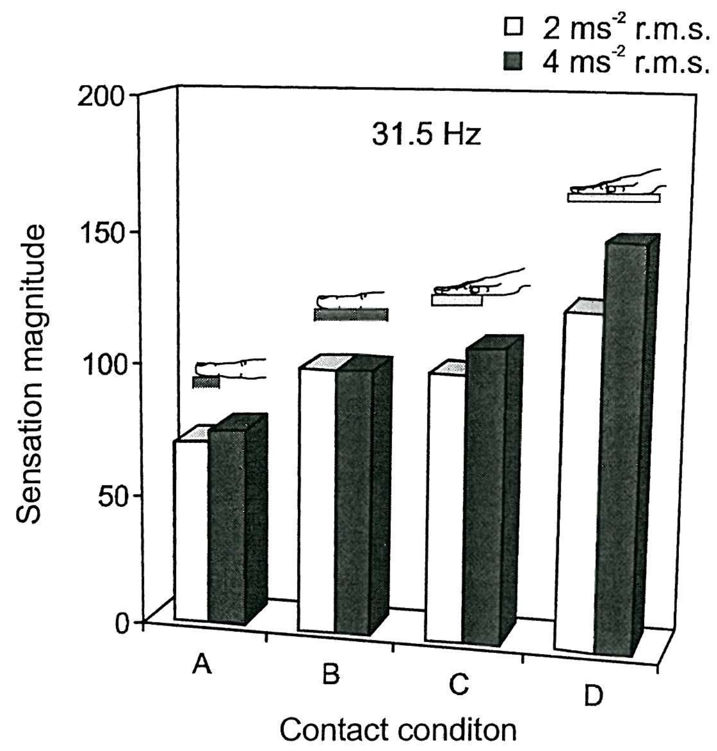


Figure 9-6 Effect of contact area on sensation magnitude measured with the 31.5 Hz vibration, relative to whole finger contact (Condition B). Medians of 20 subjects are shown.

9.5 DISCUSSION

9.5.1 Effect of frequency

The frequency dependence of the sensation magnitude observed in the current results seems consistent with other studies. Miwa (1967) produced equal sensation contours for hand-transmitted vibration from 3 to 300 Hz using a reference vibration at 20 Hz. Maeda and Iwata (1983) presented equal sensation contours for hand-transmitted vibration from 25 to 100 Hz, with a hand gripping posture. Although they used a different method, it was generally found that there was a decrease in the contours (more sensitive) with decreasing frequency and an increase in the contours (less sensitive) with increasing frequency. Some other studies have presented equal sensation contours (e.g. Reynolds *et al.*, 1977; Verrillo, 1970), with results generally consistent with the current findings, although these results were presented in other scales (displacement, velocity). A unique study by Maeda *et al.* (1983) displayed equal sensation contours on a semantic scale of discomfort and sensation magnitude for hand-transmitted vibration at various frequencies (25 to 800 Hz) and various magnitudes of acceleration (110 to 130 dB, re=10^{-6}) by using a category judgement technique. The results were similar to the equal sensation contours determined with magnitude sensation.

Results from some studies of responses to whole-body vibration are also consistent with the findings of the current study. A part of a study by Whitham and Griffin (1978) used a semantic scaling technique to obtain subjective assessments of the total vibration discomfort caused by vertical and horizontal whole-body vibration (a sitting posture) at 1.0 ms^{-2} r.m.s. with various frequencies from 2 to 64 Hz. A decreased sensitivity was found with increasing stimulus frequency. Howarth and Griffin (1988) used a cross-modality method to study the growth in sensation magnitude of low magnitude whole-body vibration (from 0.04 to 0.4 ms^{-2} r.m.s.) relative to a reference sound (1/3 octave-band noise centred at 1kHz at a sound-pressure level of 70dB). Although the frequency dependence was not significant for vertical vibration, the rate of change of subjective magnitude with increase in vibration magnitude was greater at low frequencies than at high frequencies.

A frequency dependence in the growth of sensation magnitude might give an indication that different receptors are involved in the determination of sensation at different areas of the body over a range of frequencies. As discovered in the previous study of the localisation of sensation using the same stimulus conditions to the current study, low frequency vibration at the hand was perceived as a sensation at the wrist and arm, whereas high frequency vibration was perceived where the skin was in contact with the vibrating surface (see Figures 8-2 and 8-3). This has been explained by biodynamic studies: low frequency vibration is transmitted to the wrist and arm area while vibration at high frequencies, above about 100 Hz, is localised to the hand (see Chapter 8). From the biodynamic responses, explanations for the current results were derived, especially for the low frequency responses. Because low frequency vibration is transmitted to the wrist and arm, receptors in that area may have been activated. According to a review by Pasterkamp (1999), SA II (Ruffini) and FA II (Pacinian) are sensitive to joint movements and also to have a functional role in motor control, kinaesthesia and position sense. It is possible that the transmitted vibration provided movements at the joint area and responded by SA II and FA II at the area.

The frequency dependence of the growth of sensation magnitude appears opposite to the frequency dependence of the perception thresholds, being more sensitive with increasing frequency for perception thresholds, whereas less sensitive with increasing frequency for sensation magnitudes. This might imply involvement of different mechanisms in response to vibration stimuli between threshold level and supra-threshold level: one dominant receptor type may only be responsible for determining sensation magnitude, while more than one receptor type could be excited for determining perception thresholds. The magnitudes used for determining sensation magnitudes were well above the threshold for all contact conditions. Although there was no difference in effect between the two different magnitudes (2 and 4 ms^{-2} r.m.s.), the results might alter at stimulus intensities close to threshold level.

9.5.2 Effect of contact area

In addition to the frequency effect, there was an increase in sensation magnitude with increasing contact area.

Spatial summation via the Pacinian receptors may influence sensation magnitudes: a larger population of Pacinian receptor was excited with increasing contact area from the fingertip to the whole hand. This theory assumes that the vibration stimulus at 31.5 Hz was perceived by Pacinian receptor for all contact conditions. An alternative explanation is that the increase of contact area increased transmission of vibration to other areas (e.g. wrist and arm), even with the higher frequencies. According to the previous results (see Figures 8-4 and 8-5), the localisation of sensations shifted towards the wrist and arm with increasing contact area at 31.5 Hz. The current results are restricted to 31.5 Hz, so there is a possibility that the same effect may be observed with the other frequencies.

An attempt has been made to consider the effect of contact area on the sensation magnitude results presented earlier. The data shown in Figure 9-3 have been modified by multiplying the ratio according to the results of the 'contact comparison test' (see Figure 9-6). Figure 9-7 shows the corrected sensation magnitudes, it is clearer that the sensation magnitudes reflect a form of spatial summation at all frequencies: whole hand contact was most sensitive; with decreasing sensitivity with decreasing contact area to the fingertip contact.

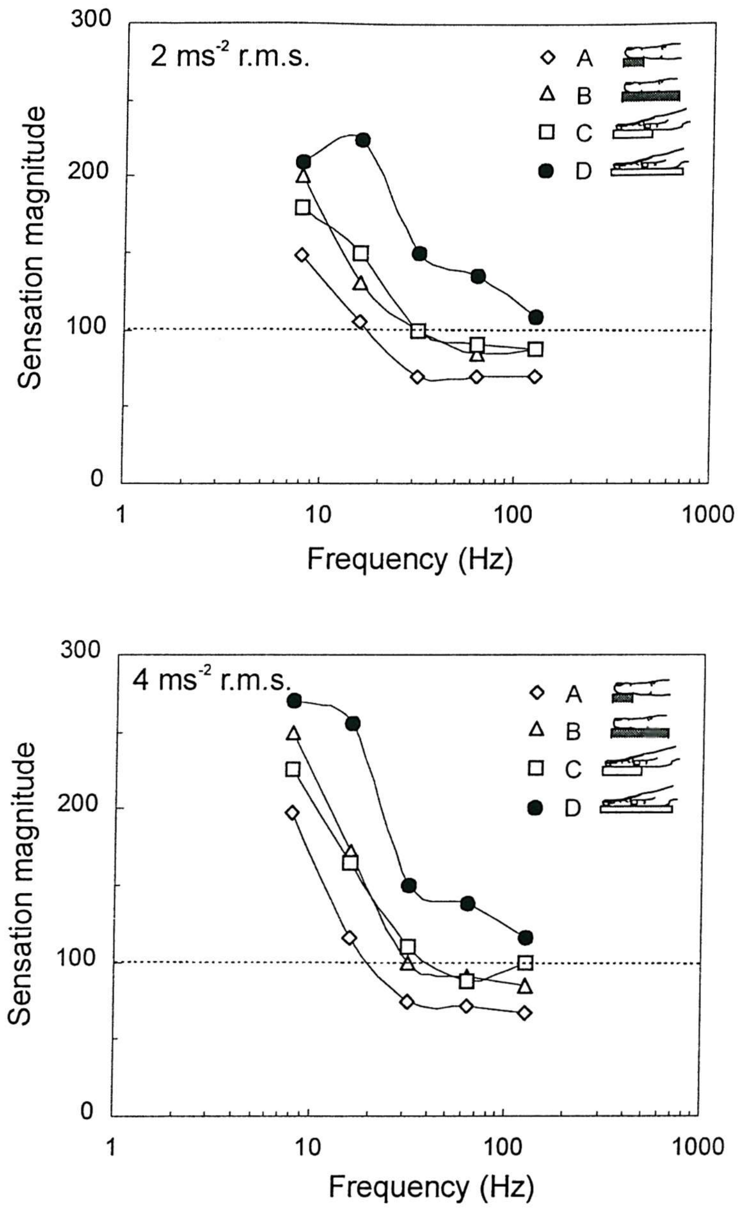


Figure 9-7 Corrected sensation magnitudes considering the effect of contact area according to the results of the 'contact comparison test'.

9.6 CONCLUSIONS

The sensation magnitudes for hand-transmitted vibration were greatly influenced by stimulus frequency and contact area:

1. The hand was more sensitive to acceleration at lower frequencies (i.e. 8 and 16 Hz), relative to the reference frequency at 31.5 Hz,
2. The hand was less sensitive to acceleration at higher frequencies (i.e. 63 and 125 Hz), relative to the reference frequency at 31.5 Hz.
3. The frequency dependence was similar with all contact areas: the sensitivity increased with increasing contact area from the fingertip to the whole hand.
4. There was no difference in response between two hand postures (i.e. a flat palm pressing and a hand gripping).
5. There was little change in the effect of contact area or vibration frequency with two different stimulus magnitudes (2 and 4 ms^{-2} r.m.s.).

The results are consistent with the results presented in the last study (Chapter 8) and may be partially explained by variations in the biodynamic transmission of vibration.

CHAPTER 10

STUDY 7 DIFFERENCE THRESHOLDS FOR INTENSITY: EFFECT OF STIMULUS FREQUENCY AND MAGNITUDE

10.1 INTRODUCTION

Identification of the perceptual mechanisms which are responsible for feeling hand-transmitted vibration may assist the improvement of vibrating hand-tools. Although many studies have investigated the sensory mechanisms by measuring vibration perception at both absolute threshold and supra-threshold levels for either the fingertip or the thenar eminence, there have been few studies for the whole-hand contacting a vibrating surface. A previous study (see Chapter 5) by the present author indicated that vibrotactile absolute thresholds as a function of frequency differed between the fingertip and the whole-hand. The follow-up study (see Chapter 10) determined masked thresholds with the fingertip and the whole hand. It was suggested that more than one receptor population would become responsible if the vibration magnitude were sufficient to be mediated by the particular receptor. The finding indicates the mechanism of perception for the whole-hand above the threshold might be unpredictable, differing from the mechanism at the threshold level or, at least, not fully known.

Difference thresholds (difference limen = DL) is the just-noticeable difference in a stimulus magnitude. Difference thresholds for the intensity of vibration stimuli is one of the techniques quantifying perception at the supra-threshold level and have been measured by several sensory investigators. The basic idea proposed by EH Weber was that difference thresholds are proportional to the magnitude of the stimulus, the relation is expressed by Weber's Law:

$$\Delta I/I = \text{constant}$$

where ΔI is the difference threshold in a stimulus of intensity I. According to the law, difference thresholds increase with increasing magnitudes of vibration stimuli. However, exposures to hand-transmitted vibration are complex and vibration magnitudes cannot be quantified simply. The magnitude of tool vibration may change from moment to moment, containing both low magnitudes of vibration and very high magnitudes of shock. The vibration on tools also contains a variety of characteristics with different frequencies and dominant axes.

10.2 OBJECTIVES

The objectives of this study were:

- To determine difference thresholds for the intensity (i.e. magnitude) of hand-transmitted vibration with a handle grasping posture.
- To examine the effects of both vibration magnitude and frequency; difference thresholds were obtained at seven frequencies (8 to 500 Hz) and at two magnitudes (2.0 and 5.0 ms^{-2} r.m.s.) of hand-transmitted vibration. It was hypothesised that the difference thresholds would be proportional to the magnitude of the vibration stimuli, and would be dependent on vibration frequency.

10.3 EXPERIMENTAL DESIGN

10.3.1 Subjects

Eight healthy male volunteers (aged between 23 and 28 years), staff and students of the University of Southampton, participated in the experiment. All subjects were non-smokers, right handed and free of occupational exposure to hand-transmitted vibration. Subjects were asked not to consume caffeine or alcohol for at least two hours prior to the tests. Finger skin temperature was measured before the threshold measurements, because there is a significant change in vibrotactile sensitivity with temperature (Bolanowski and Verrillo, 1982), although difference thresholds at the thenar eminence have been found to be unaffected by skin-surface temperature (Gescheider *et al.*, 1997); tests proceeded if the skin temperature was higher than 29° Celsius.

10.3.2 Apparatus

Sinusoidal hand-transmitted vibration was produced using a Derritron VP4 electrodynamic vertical vibrator powered by an amplifier via a load dissipating resister to reduce unwanted vibration noise at 50 Hz to below the absolute threshold level, less than 0.01 ms^{-2} r.m.s. A wooden-handle (30 mm diameter) was fixed to the vibrator. A piezo-electric accelerometer (DJ Birchall, type A/20 T) was placed on the middle area of a wooden surface beneath the handle. The analogue signals from the accelerometer were passed through a charge amplifier (Brüel & Kjær, type 2635) and via a low-pass filter adjusted according to the sampling rate. A data acquisition and analysis system, *HVLab*, was used to control the shaker and to acquire the signals from the accelerometer, using sampling rates between 400 and 8065 samples per second varying according to the excitation frequency.

Due to audible acoustic noise from the vibrator accompanying the excitation frequencies of 125 Hz, 250 Hz and 500 Hz, subjects were exposed to a masking noise via a pair of headphones in order to prevent them from hearing the vibration. The masking noise consisted of a square wave adjusting separately at 125 Hz, 250 Hz or 500 Hz using a function generator (Feedback, type FG600) mixed with white noise at 70 dB(A). The sound levels from the headphones were measured using 'KEMAR' (Knowles Electronics Manikin for Acoustic Research). The noise exposure levels for an undisturbed field equivalent were 71.6, 74.0 and 77.1 dB(A) on the right ear and 69.8, 72.5 and 75.1 dB(A) on the left ear at 125, 250 and 500 Hz, respectively. Although there was no noticeable noise from the vibrator when excited at frequencies of 63 Hz and lower, subjects were exposed to the same masking noise as at 125 Hz. A light was provided to indicate when a vibration stimulus was being presented.

10.3.3 Procedure

The difference thresholds were determined at two vibration magnitudes (2 and 5 ms^{-2} r.m.s., unweighted) in two separate sessions. Each session consisted of seven tests examining seven frequencies in the range from 8 to 500 Hz (at the preferred octave centre frequencies).

Additional tests were performed with two of the eight subjects so as to measure difference thresholds for hearing sound from the vibrator with the masking noise presented via headphones (i.e., without holding the handle) so as to confirm that the difference thresholds for vibration intensity were not detected from the differences in the associated sounds. With both subjects, three tests were conducted at excitation frequencies of 125, 250 and 500 Hz with the 5 ms^{-2} r.m.s. reference vibration magnitude.

10.3.4 Hand posture

During the measurements, the hand posture was controlled as shown in Figure 10-1. A handle grasping posture was chosen because the previous study (Chapter 5) found no difference in perception threshold between a whole hand pressing posture and a handle grasping posture, and it was thought the grasping posture would give more practical apprecation. Subjects were asked to grasp the wooden-handle (30 mm diameter) with no grip force and to push downward with a force of about 10 N. The subjects' arms were supported by an armrest so as to fix the arm posture and the arm height.

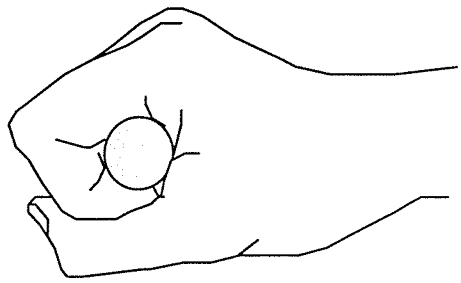


Figure 10-1 Handle grasping hand posture.

10.3.5 Difference threshold testing algorithm

A psychophysical method, 'Up-and-Down Transformed Response (UDTR) method', proposed by Wetherill and Levitt (1965), was employed for the measurements. The procedure is adaptive so that the performance of the subject is used to adjust automatically the stimulus magnitude around the threshold level. The UDTR procedures are extensively used in psychoacoustics testing since there are some advantages with simplicity, high-efficiency, robustness, small-sample reliability, and relative freedom from restrictive assumptions (Levitt, 1971), although appropriate corrections for bias are required for good estimations (Leek *et al*, 1992). The method is known as the *staircase method*: if a subject can detect a stimulus, the intensity of the stimulus is decreased by a particular amount. The UDTR method makes it possible to obtain estimates of positive responses other than a 50% response by changing the up and down sequential rule.

In this experiment, a three-down one-up rule was employed so as to determine the 79.4% probability of correct response. The two-alternative forced-choice tracking procedure was applied so that subjects simply compared two stimuli. In a test, subjects were exposed to a series of trials, a trial consisted of two sinusoidal motions: a 2 second period of a 'reference' stimulus and a 2 second period of a 'test' stimulus, separated by a

1 second 'pause'. The magnitude of the 'reference' stimulus was fixed at either 2.0 or 5.0 ms^{-2} r.m.s., depending on the condition being tested. The 'test' stimulus was set at a greater magnitude than the 'reference', commencing with a 1 dB magnitude difference. The order of the 'reference' and 'test' stimuli was randomised. The task of subjects was to judge whether the first or the second stimulus was greater. If the response was incorrect, then the 'test' magnitude was increased by 0.25 dB (i.e. multiplied by 1.03). If three consecutive responses were correct, then the 'test' magnitude was decreased by 0.25 dB (i.e. divided by 1.03). The vibration acceleration on the handle during every 'test' and 'reference' stimulus was recorded using the *HVLab* system. A test was terminated after six reversals (a point where the stimulus level reversed direction), often after presenting approximately 25 to 40 trials, lasting 5 to 7 minutes.

10.3.6 Algorithm for determining difference thresholds

A typical test sequence is illustrated in Figure 10-2. In the example, incorrect responses were given after trials No. 1 and 3, so the next stimulus intensities were increased. After trials No. 4, 5 and 6, three consecutive correct responses had been given, so the next stimulus intensity was decreased. According to the rule, three 'peaks' and three 'troughs' were required in a test; the data used for the analysis were these six reversal points (data shown with boxes in Figure 10-2). A threshold value was determined from the mean of the values taken from the 'peaks' and 'troughs' at the six reversals. The 'reference' magnitudes were measured each trial of the threshold measurement. The difference threshold was obtained by subtracting the mean of the 'reference' magnitudes from the threshold value:

$$\text{Difference threshold} = \frac{\left[\sum_{i=1}^{i=3} p_i + \sum_{j=1}^{j=3} t_j\right]}{N} - R$$

where p_i is the vibration magnitude of peak i, and t_j is the vibration magnitude of trough j; N is the number of reversals (=6); R is the mean reference magnitude.

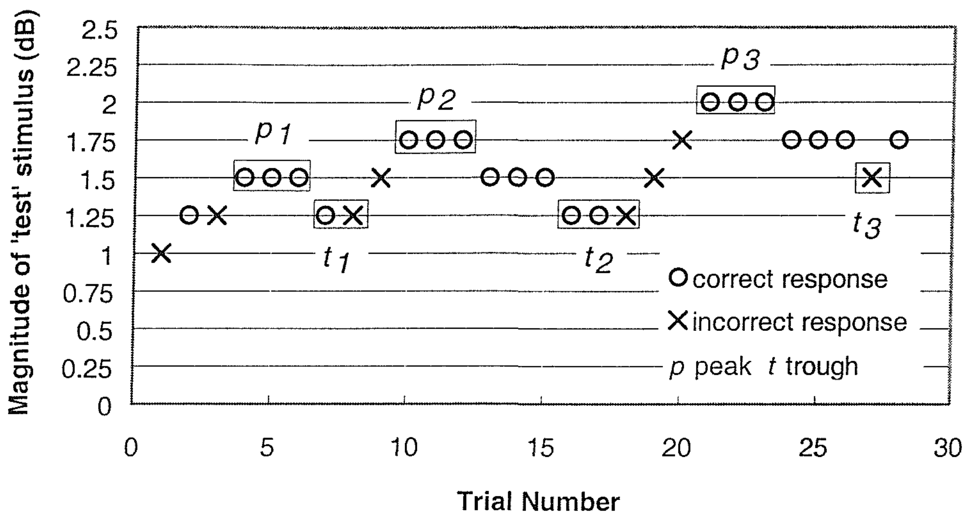


Figure 10-2 Typical data for the UDTR procedure (three-down one-up rule).

10.4 RESULTS

10.4.1 Difference thresholds: effect of vibration magnitude and frequency

Difference thresholds were expressed in r.m.s. acceleration. Figure 10-3 shows the individual threshold data and medians for each of the eight subjects plotted as a function of frequency. A summary table of the difference thresholds for each of the eight subjects is listed in Appendix E8-1. It is seen that the difference thresholds at the high reference magnitude (5 ms^{-2} r.m.s.) were greater than those at the low reference magnitude (2 ms^{-2} r.m.s.). The individual difference thresholds ranged from 0.160 to 0.761 ms^{-2} r.m.s. at the low reference magnitude and from 0.295 to 1.796 ms^{-2} r.m.s. at the high reference magnitude. The corresponding standard deviations over subjects ranged from 0.046 to 0.159 ms^{-2} r.m.s. and 0.157 to 0.442 ms^{-2} r.m.s., respectively. As shown in Figure 10-3, virtually flat contours were obtained in difference thresholds when presented in terms of acceleration thresholds as a function of frequency at both the low and the high reference magnitudes. There were no significant differences in thresholds between the seven frequencies (Friedman, $p>0.05$), although a marginal significant difference was observed at the low reference magnitude (Friedman, $p=0.08$).

The additional hearing tests with two subjects showed that difference thresholds when listening to the noise from the vibrator without holding the handle (with masking noises at either 125, 250 or 500 Hz) were all higher than their vibration detection thresholds. When the handle was held by the hand the noise level was decreased; further, during the

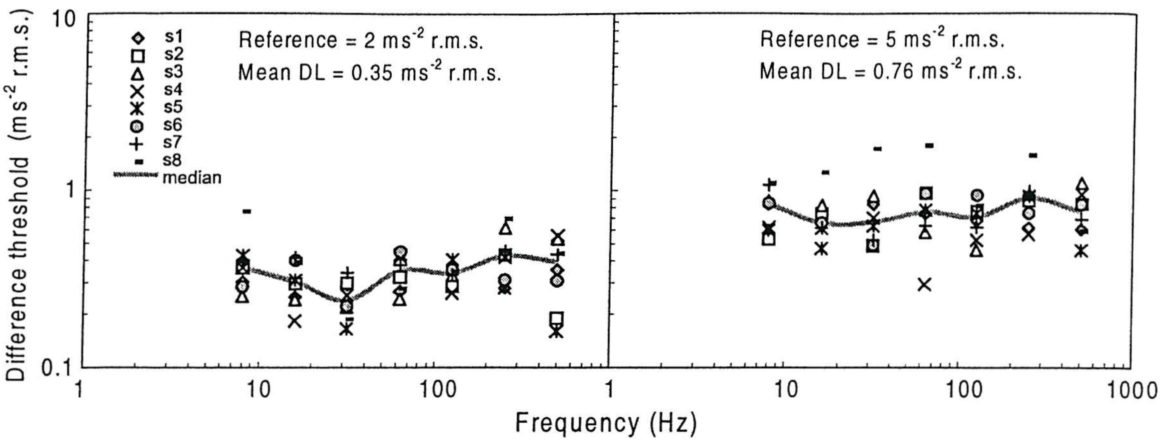


Figure 10-3 Difference thresholds for eight subjects in two reverence magnitudes. The grey lines show median thresholds.

experiment, it was necessary for the subjects to concentrate on vibration detection since even without the masking noise there was no discernible noise from the vibrator at most frequencies. It is therefore concluded that the noise due to vibration excitation did not affect the vibration difference thresholds.

There were no significant associations between difference thresholds and skin temperature, subject age or body size (i.e., weight and height) (Spearman, $p>0.05$).

10.4.2 Weber fraction (Relative difference thresholds)

The 'absolute difference thresholds' were expressed as 'relative difference thresholds' using the Weber fraction, $\Delta I/I$ (i.e. the absolute difference threshold, ΔI, divided by the reference magnitude, I). Figure 10-4 shows the median and inter-quartile ranges of the Weber fractions calculated from the difference thresholds given by the eight subjects. The relative difference thresholds varied between subjects (from 5.9 to 36.8%) with mean thresholds of 18.1% at the low reference magnitude and 15.1% at the high reference magnitude. There was no significant difference in relative difference thresholds between vibration frequencies (Friedman, $p>0.1$), or between reference magnitudes (Wilcoxon, $p>0.1$) at any frequency. However, at higher frequencies such as 125, 250 and 500 Hz, it was noted that relative difference thresholds were slightly greater at the low reference magnitude (mean 18.6%) than at the high reference magnitude (mean 15.6%).

10.5 DISCUSSION

When the magnitude of hand-transmitted vibration was increased, the difference thresholds also increased, with no significant dependence on vibration frequency. Figure 10-5 shows a comparison of absolute threshold contour with difference thresholds, both measured with handle-grasping posture. It is surprising that the difference thresholds were not dependent on vibration frequency like absolute perception thresholds.

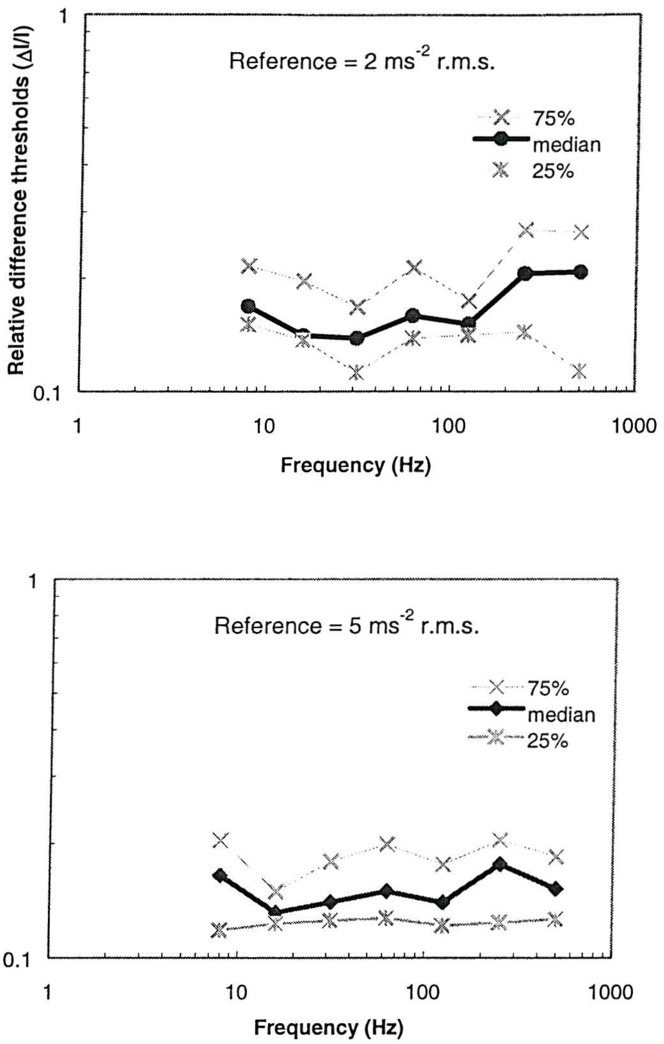


Figure 10-4 Median of relative difference thresholds (Weber fraction) as a function of frequency at two reference magnitudes, data are shown with inter-quartile ranges (25% and 75%).

A variation in relative difference thresholds with vibration magnitude has been found in previous studies whereby *ΔI/I* is greater when *I* is low and gradually decreases as *I* is increased; the effect has mainly been examined at 250 Hz at the thenar eminence (Gescheider *et al.*, 1990, 1994, 1996a,b, 1997). The phenomenon might be explained by the mediation characteristics of mechanoreceptors; it is agreed that vibration stimuli at higher frequency are detected by the 'Pacinian' system, but it is assumed that when the vibration intensity reaches some magnitude, the vibration detection is mediated by both 'Pacinian' and 'non-Pacinian' systems. According to the results from Gescheider *et al.*, (1997), the magnitude required for 'non-Pacinian' perception at 250 Hz was a sensation level of 25 dB (25 dB greater magnitudes than the absolute threshold level); their difference thresholds were lower when the vibration magnitude exceeded this level. In order to investigate this assumption, the reference magnitudes used in the present experiment were converted to the sensation levels using the absolute threshold data previously determined by the present author in Study 5. The sensation levels for reference magnitudes of 2 and 5 ms^{-2} r.m.s. acceleration at 250 Hz were equivalent to 43.1 dB and 51.1 dB, respectively (i.e. an absolute threshold of 0.014 ms^{-2} r.m.s). For vibration magnitudes above 25 dB sensation level, Gescheider *et al.* (1997) found relative difference thresholds of about 13 to 16% using 250 Hz vibration at the thenar eminence, which was similar to the values of 15.6 and 18.6% in the present study. However, it was not possible to observe any effects below 25 dB of sensation level in the present study.

An implication of the intensity-dependence of difference thresholds is that the discrimination sensitivity of the 'Pacinian' system is less than that of the 'non-Pacinian' system. The relative difference thresholds will then not decrease with increasing the vibration magnitudes at lower frequencies, consistent with the results of the present experiment (see Figure 10-4). At higher frequencies, when vibration stimuli are of sufficient magnitude to be mediated by both the 'Pacinian' and the 'non-Pacinian'

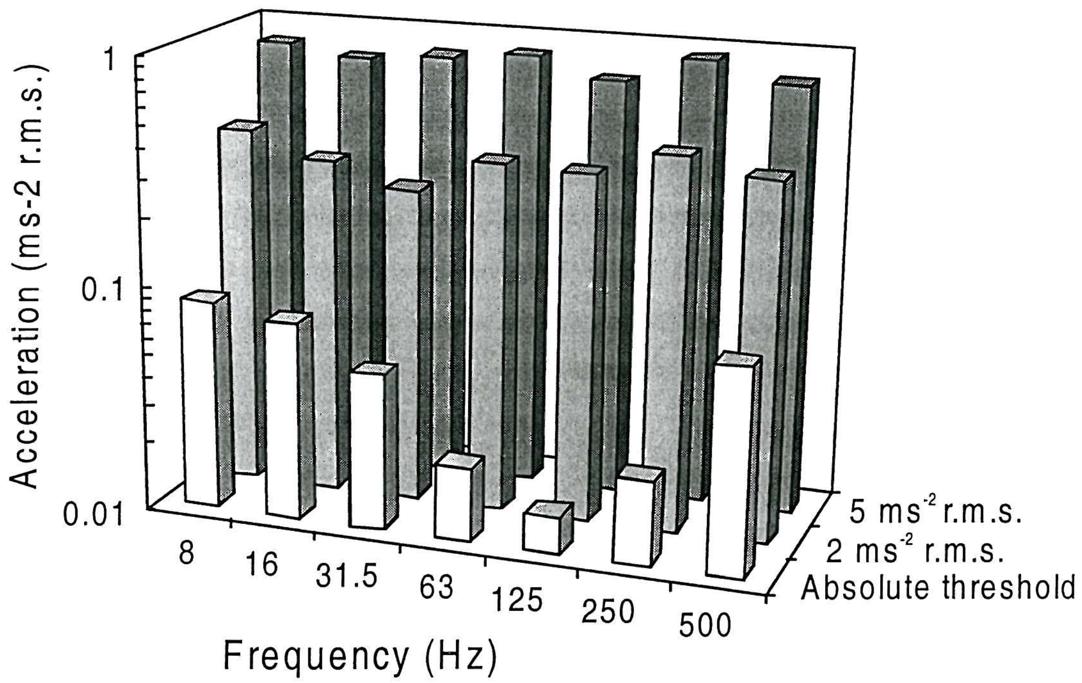


Figure 10-5 Comparison of threshold contours: absolute thresholds and difference thresholds. Absolute threshold data used from the results of Study 2. The same contact conditions (handle-gripping posture, 10 N push force with no grip force) were applied.

systems, the difference thresholds may be lower due to superior detection by the 'non-Pacinian' system. In these conditions, when the stimulus intensity is increased, the response of the 'Pacinian' system tends to be saturated (Bolanowski *et al.*, 1992), so threshold discrimination may be performed entirely by the 'non-Pacinian' system with high magnitude stimuli. This 'dominate of non-Pacinian system' theory can be supported by Gescheider *et al.* (1997) that the relative difference threshold was unaffected by skin temperature, which implies absence response via Pacinian system as the sensitivity of the Pacinian system is dependent on skin temperature.

At low frequencies, there may have been perception of the stimuli other than though the mediation of the 'Pacinian' and the 'non-Pacinian' systems. At 8 Hz, most subjects perceived the vibration difference in the arms rather than in the hand. The vibration displacements at low frequencies were much greater than at higher frequencies (e.g. the 5 ms^{-2} r.m.s. reference magnitude had a vibration displacement of 5.6 mm peak-to-peak). This displacement at the hand resulted in significant movements of the arm (moderated by any resonance in the hand-arm system) that may have been perceived within the arm or via contact with the fixed arm support. Other factors involved to the detection sensitivity at 8 Hz may include visual perception.

10.6 CONCLUSIONS

The difference thresholds were almost proportional to stimulus magnitudes from 2 to 5 ms^{-2} r.m.s., with no significant dependence on vibration frequency. Relative difference thresholds, Weber fraction, were determined and found a constant ratio ($\Delta I/I$ = 0.15 to 0.18) over two different stimulus magnitudes, which supported a consistence with Weber's Law. Subtle differences observed in difference thresholds at high frequencies such as 125, 250 and 500 Hz may be due to the mediation characteristics of the 'Pacinian' and the 'non-Pacinian' systems.

CHAPTER 11

STUDY 8 MASKED THRESHOLDS: INDEPENDENT RESPONSES OF PACINIAN AND NON-PACINIAN RECEPTORS

11.1 INTRODUCTION

The previous studies of absolute thresholds (Studies 1, 2, 3 and 4) presented the frequency dependence of absolute thresholds over the range 8 to 500 Hz, indicating mediation by at least two different receptors. This was evident in the results of Study 3 examining the effect of a surround (see Chapter 6): the threshold sensitivity altered with and without the surround over the frequency range. The Pacinian system is said to be capable at high frequency of integrating sensitivity over the contact area, whereas the non-Pacinian system has increased sensitivity at low frequency when excited by a gradient stimulus (e.g. a surround around the probe). However, the results from whole hand contact were not always explained by the known characteristics of the receptor systems.

The other finding from Study 3 was difficult to interpret: the thresholds decreased with increasing contact area from the fingertip to the whole hand at low frequencies as well as at high frequencies. Could this have been due to spatial summation via the Pacinian system? Or is there some other factor affecting detection sensitivity?

At supra-threshold vibration levels, it seems there is a frequency dependence in the subjective responses. In Study 6, sensation magnitudes determined at 2 and 4 ms^{-2} r.m.s. showed almost the opposite frequency response to that for absolute thresholds: most sensitivity to acceleration at lower frequencies and less sensitivity at higher frequencies (see Chapter 9). Difference thresholds determined in Study 7 using magnitudes well above threshold level (i.e. 2.0 and 5.0 ms^{-2} r.m.s.) presented no dependence on stimulus frequency over the range 8 to 500 Hz (see Chapter 10).

These two studies were conducted well above the threshold level of the Pacinian and non-Pacinian system receptor systems. The findings might be explained by two alternative assumptions: either (1) responses were dominated by a single receptor system; or (2) responses were mediated via different receptors.

In order to interpret the findings and produce a sensory model of hand-transmitted vibration, it seems necessary to consider three questions:

a) Which receptor initially mediates perception when determining absolute thresholds?

b) What magnitude of vibration is required to stimulate other receptors?

c) How does the response (i.e. sensitivity) of each receptor differ with changing skin-stimulus contact conditions?

In the previous studies, the term 'Pacinian system" and "non-Pacinian system" were used to explain the mechanisms of perception in various conditions, rather than referring to particular tactile afferent units (i.e. FA I, SA I and SA II). This was partly because the non-Pacinian receptors are less easily identified than the Pacinian receptors, so it was not certain form the threshold results which particular non-Pacinian receptor responded to the vibration stimuli.

The Pacinian system has well known distinctive characteristics, capable of spatial and temporal summation and dependent on temperature (see review from Gescheider, *et al.*, 1978). It is also well documented that Pacinian corpuscles (i.e. FA II) are the inputs to the Pacinian system (Bolanowski and Verrillo, 1982; Mountcastle *et al.*, 1972; Verrillo, 1966d). As for the non-Pacinian system, probably including the Meissner, Merkel and Ruffini corpuscles (i.e. FA I, SAI and SA II, respectively), there are a few studies showing two or three separate responses in the non-Pacinian system (Bolanowski *et al.*, 1988; Capraro *et al.*, 1979; Gescheider *et al.*, 1985; Verrillo and Bolanowski, 1986). They employed a technique using vibration masking stimuli to elicit independent receptor responses in the non-Pacinian systems. The masking function (detection of the test stimulus is impaired by a masking stimulus) is known to occur only when the masker and the test stimulus excite the same receptor channel (Gescheider *et al.*, 1982; Hamer, 1979; Hamer *et al.*, 1983). If the masker and the test stimulus stimulate different receptors, no masking occurs. Studies have employed vibrotactile masking as a tool to selectively explore the sensitivity one psychophysical receptor channel. By varying the intensity and the frequency of the masking stimulus and the frequency of the test stimulus, it is possible to differentiate independent receptor channels.

The masking functions determined in previous studies have used specific contact conditions that were different from the studies in this research. They employed a 'manipulative' method, applying a small stimulus contactor with a surround on the finger or the thenar eminence: they minimised the contact area in order to minimise the spatial summation effect of the Pacinian system, and produce a sharp gradient to evoke the non-Pacinian system. It is therefore uncertain how the individual non-Pacinian receptors contribute to vibrotactile perception in 'normal' touch.

In this chapter, sensory mechanisms for hand-transmitted vibration were explored on the basis of the sensory model produced from the previous studies. A laboratory experiment was then conducted using the masking technique to test the hypotheses.

11.2 MASKING THEORY

11.2.1 Masking functions

Masking is a phenomenon in which the perception of a normally detectable stimulus (i.e. test stimulus) is impeded by a second stimulus. The second stimulus may be presented at the same time as the test stimulus (i.e. simultaneous masking), alternatively it may be presented at a different time either before (i.e. forward masking), or after (i.e. backward masking) of the test stimulus.

The masking effect is well-known in auditory psychophysics. Research has revealed that when a tone is masked by noise, only the frequencies in the noise close to the frequency of the tone cause masking. The range of frequencies in the noise that mask a pure tone signal, and act as a masker, is called the 'critical band'. The masking functions for vibratory stimuli are not the same as auditory stimuli. It has been found that masking only occurs if two different stimuli excite the same receptor channel (Gescheider, 1982; Gescheider *et al.*, 1985; Hamer, 1979; Hamer *et al.*, 1983; Labs *et al.,* 1978; Verrillo *et al.*, 1983), because neural activity in one receptor channel cannot affect the detection ability of another receptor channel. The two basic masking functions are defined as 'within-channel masking' and 'cross-channel masking'.

11.2.1.1 Within-channel masking

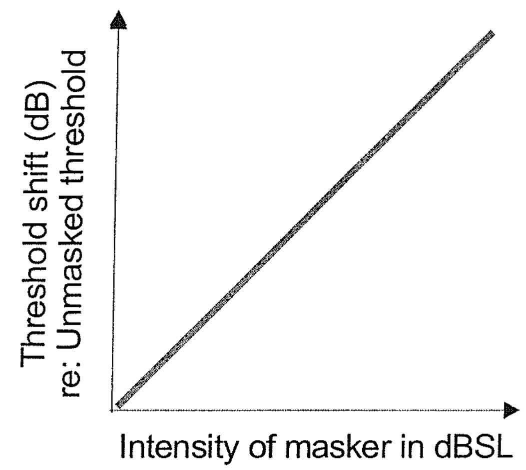


Figure 11-1 Within-channel masking function

If masker and test stimulus are detected by the same receptor channel, the amount of masking should increase linearly as a function of the intensity of the masker (see Figure 11-1). If only a single receptor channel is responsible for vibration perception, masking should occur at any frequency and with any magnitude of masking stimulus.

Gescheider and O'Malley (1983) demonstrated within-channel masking using the same centre frequency of the masker as the test stimulus.

Previous research has shown that the slope of the masking function depends on the presentation of masking stimuli: simultaneous masking produces a slope of 1.0 for both high frequency (Gescheider *et al.*, 1982) and low frequency (Hamer, 1979) masking of a test stimulus, but forward masking produces a slope of 0.70 for high frequency and 0.83 for low frequency stimuli (Gescheider *et al.*, 1983). This is due to the type of masking stimulation (i.e. forward or backward masking), delaying the onset of the test stimulus could reduce the amount of masking. According to a study by Gescheider *et al.* (1983), a greater reduction in threshold shift may occur in the Pacinian than in the non-Pacinian system.

11.2.1.2 Cross-channel masking

The response functions for vibratory stimuli are complex. It is agreed by many researchers that at least two distinct receptors are involved in the detection of vibratory stimuli. These can be simply distinguished as Pacinian and non-Pacinian systems. Masking will not show if the masking stimulus is detected by the Pacinian system when the test stimulus is only exciting the non-Pacinian system, or vice-versa (Labs *et al.,* 1978; Hamer, 1979; Hamer *et al.*, 1983; Gescheider, 1982; Verrillo *et al.*, 1983).

If the vibration stimulus excites two systems, but they have different sensitivities in detection, the masking function will look like either of the two graphs (i.e. Example A and Example B) shown in Figure 11-2.

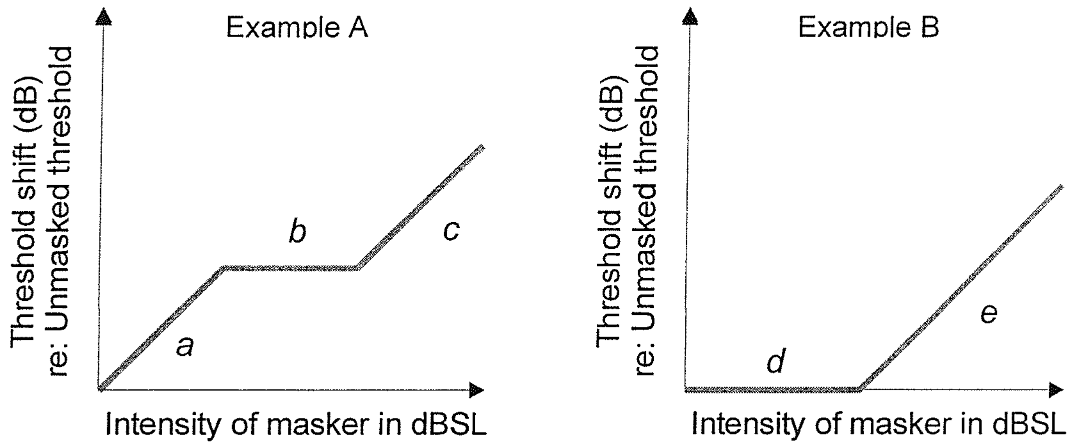


Figure 11-2 Cross-channel masking functions

Example A:

The threshold of the test stimulus is increased with increasing intensity of the masker (line *a*). With increasing masker intensity, the test stimulus begins to excite the other system (i.e. non-Pacinian system) so that the masking function shows no threshold shift (line *b*). With further increases in the masker intensity, the masker reaches the threshold of the non-Pacinian system, which results in re-appearance of the masking (line *c*).

Example B:

In the case in which the two stimuli are initially detected by different receptors, (suppose the Pacinian for the masker, the non-Pacinian for the test stimulus), thresholds of the non-Pacinian system will not be affected by the masking stimulus until the masker reaches the threshold of the non-Pacinian system (line *d*). The masker stimulus then also excites the non-Pacinian system so that masking occurs (line *e*).

11.2.2 Determination of receptor thresholds from masking functions

Once the masking functions are obtained, it is possible to determine the threshold of each single independent receptor channel. According to the masking theory explained in the previous section, when the frequencies of the masker and the test stimulus are different, the masking function will be a combination of two functions: (i) masking increases continuously when both the masker and the test stimulus are perceived by one receptor channel, (ii) masking does not occur when the masker and the test stimulus are perceived by two different receptor channels.

Figure 11-3 illustrates an example of the determination of detection thresholds of two receptor channels based on the duplex model of vibrotactile perception. With a low frequency masker at 16 Hz (Graph A[1] of Figure 11-3), the masker is initially mediated by the non-Pacinian system (NP). Masking will show if the test stimulus is also initially mediated by the same system as the masker (NP), which is a 31.5 Hz test stimulus (see Graph A[2]) showing elevation of the non-Pacinian threshold, the amount is marked as 'A' and 'a' on the graph. Then, no masking will occur while the test stimulus begins to excite the Pacinian system (marked as 'B'). Increasing the masker intensity further, the masker also begins to excite the Pacinian system so a masking occurs again (marked as 'C' and 'c'). Looking at the other test frequency (i.e. at 63 and 125 Hz), the Pacinian system (P) is initially mediated so that no masking will show (marked as 'B') until the masker reaches the threshold for the Pacinian system to start masking (marked as 'C' and 'c').

In the reverse way, the same procedure can be employed with a high frequency masker at 125 Hz (see Graph B[1] of Figure 11-3). The masker is now mediated by the Pacinian system so that masking will be seen at the beginning when the test stimulus is 63 Hz. There is no masking with the test frequencies at 31.5 and 16 Hz (marked as 'A' and 'B') until the masker starts to excite non-Pacinian system (marked as 'C' and 'c').

It is possible that more than two flat horizontal lines appear when increasing the intensity of a masker. This indicates that more than three receptors are involved in mediating the vibratory stimuli, suggesting there are independent receptors in the non-Pacinian system. This technique will therefore allow the determination of the thresholds of individual receptors and might allow the identification of the sensitivity of each receptor within the non-Pacinian system.

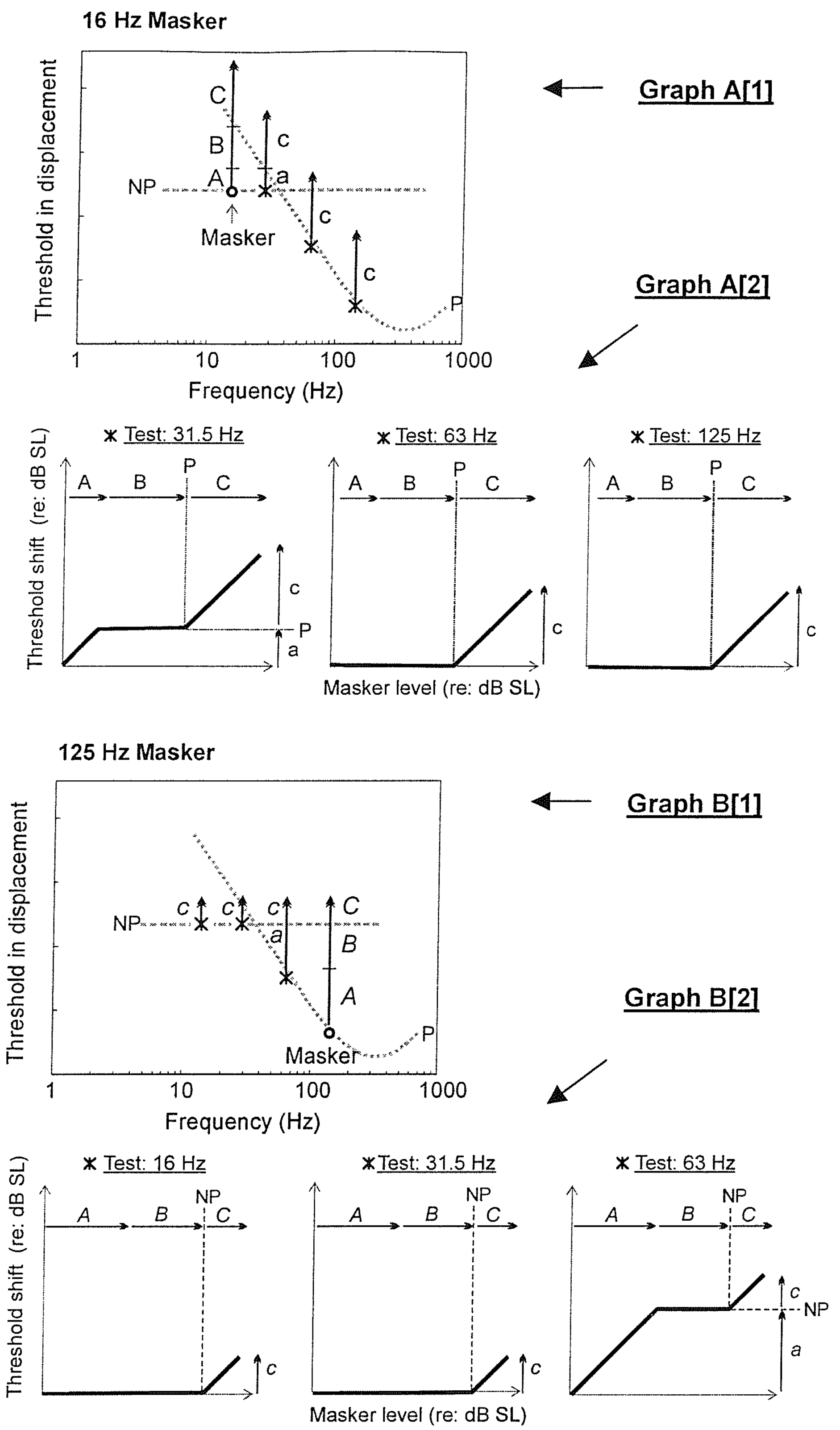


Figure 11-3 Illustration of how the receptor thresholds are determined from the masking functions. The duplex model is assumed for the predictions.

11.3 HYPOTHESES

11.3.1 Triplex model

The non-Pacinian system includes all receptors other than the Pacinian corpuscles, which are believed to be FA I, SA II and SA II. Gescheider *et al.* (1985) proposed a triplex model with two separate receptors in the non-Pacinian system (i.e., FAI (NPI) and SAII (NPII)) presenting detection threshold contours of each receptor. The adapted data from Gescheider *et al.* (1985) are shown in Figure 11-4.

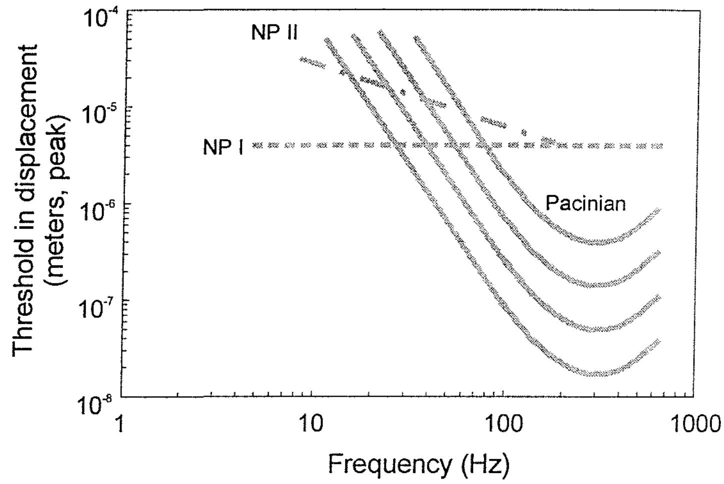


Figure 11-4 Triplex model of detection sensitivity (Figure reproduced from Gescheider *et. al.*, 1985)

The triplex model was presented by Gescheider *et al.* (1985) in a simple way using a displacement scale. The absolute threshold contours obtained with three different contact conditions from the previous studies (Studies 2 and 3) are shown in the left graph in Figure 11-5 and are re-plotted on a displacement scale in a right graph in Figure 11-5. It is

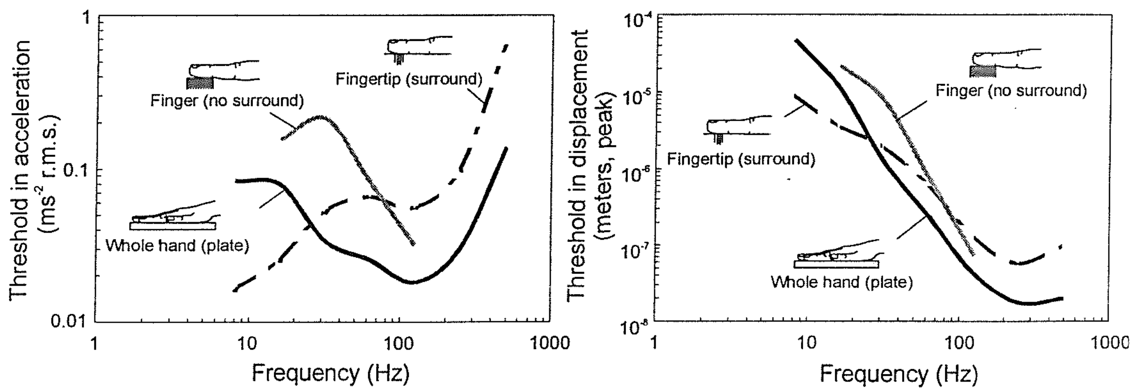


Figure 11-5 Absolute thresholds obtained with three contact conditions. Threshold data from Studies 2 and 3.

seen that the U-shaped contours around the high frequency range show the deepest curve with whole hand excitation, which is rather similar to the Pacinian model in Figure 11-4. In order to see the low frequency functions more clearly, the threshold contours were overlaid on the triplex model and are shown in Figure 11-6. The threshold contours trace over the three lines of response functions representing the Pacinian, NPI and NPII systems. It is clearly seen that thresholds at high frequency (above 30-50 Hz) follow the Pacinian curve with both the finger and the whole hand conditions. Even with the fingertip condition with a surround to reduce Pacinian response, the threshold contour is still similar to the Pacinian curve at frequencies above 80 Hz. At low frequencies the threshold contours, suggest that two different receptors in the non-Pacinian system (i.e. NP I and NP II) may contribute to absolute thresholds, depending on the contact condition applied:

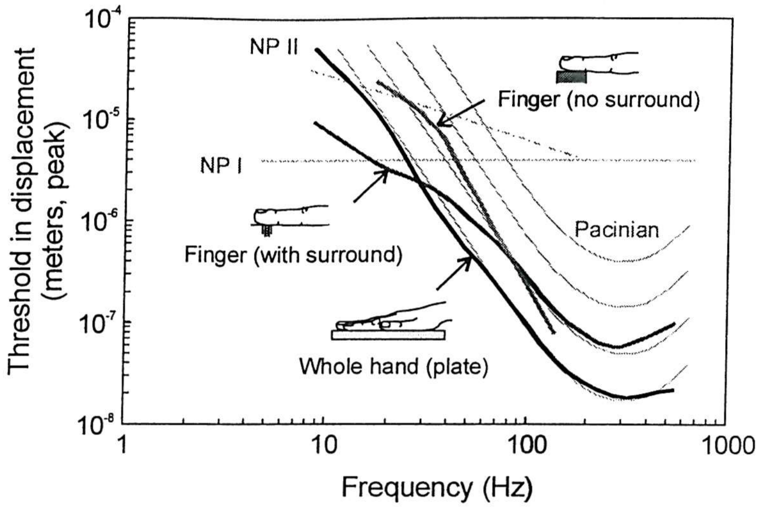


Figure 11-6 Absolute threshold contours overlaid on the triplex model. (Data from Studies 2 and 3)

Whole hand thresholds	NP II curve is followed below about 20 Hz
Finger (no surround) thresholds	NP II curve is followed below about 40 Hz
Finger (with surround) thresholds	NP I curve is followed below about 30 Hz

The triplex model was produced by an experiment using restricted contact conditions, with a very smaller probe diameter (i.e. 0.01 cm^2) at the thenar eminence in order to eliminate the effect of the Pacinian receptors. It is possible that the sensitivity of the NP I and NP II receptors may change with different contact conditions. No study has yet demonstrated whether the NP I (i.e. FA I) or NP II (i.e. SA II) receptors influence absolute thresholds when vibration is applied with the finger and the whole hand.

The hypotheses of the current experiment were based on the triplex model, assuming that three receptors are responsible for detecting vibration stimuli applied with a normal touch. Independent responses within the non-Pacinian system may be observed with masked thresholds, even when gradient stimuli (such as a surround around the probe) are absent on the glabrous skin of the hand. In other words, the response of the NP I receptors may become insensitive if no gradient stimulus is present.

11.4 OBJECTIVES OF EXPERIMENT

A laboratory experiment was designed with three objectives:

- To determine masked thresholds using simultaneous masking with various frequencies and magnitudes of masker and various frequencies of test stimuli.
- To identify the receptors responsible for absolute thresholds at the fingertip and the whole hand.
- To estimate perception threshold contours for other receptors at supra-threshold levels.

11.5 EXPERIMENTAL METHOD

11.5.1 Subjects

Six healthy paid volunteers (five males and one female), aged between 18 and 27 years (mean 23.2 years, SD = 2.94), took part in the study. The average stature and average weight of the six subjects were 176.7 cm (SD = 7.6) and 72.8 kg (SD = 12.8), respectively. They were all non-smokers, right handed and had no history of occupational exposure to hand-transmitted vibration. Their hand and finger dimensions (i.e. hand length, hand breadth, hand depth, finger length, digit length, and digit breadth, see Section 5.3.2 for the details) were also measured to determine whether there were any correlations with the measured thresholds.

11.5.2 Skin-stimulus contact conditions

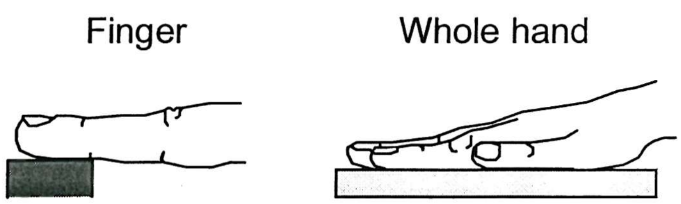


Figure 11-7 Finger and whole hand contact conditions employed in the study.

Vibration stimuli were delivered either to the distal phalanx of the middle finger or to the whole hand, with fixed postures as shown in Figure 11-7. The contact conditions were the same as employed in Chapter 6 (see Table 6-2: Condition D for the finger condition and Condition H for whole hand condition). An electrodynamic vibrator, VP 30, was used for both conditions. The downward contact forces applied by the finger and the hand were 1N and 5 N, respectively. A height adjustable armrest was provided to maintain a fixed hand posture during the measurement.

The skin temperature of the subject's fingertip (middle finger) was measured at the beginning of every session, and the measurements only proceeded if the skin temperature was higher than 29 °Celsius.

11.5.3 Stimulus conditions

Sinusoidal vibratory stimuli, 600 ms in duration, with rise-fall times of 100 ms were used as test stimuli. Four frequencies of the test stimulus were prepared ranging from 16 to 125 Hz. The masking stimulus, 3000 ms in duration, was created with 1/3 octave bandwidth vibration at either 16 Hz (range between 14.1 and 17.8 Hz) or 125 Hz (range between 112 and 141 Hz). The magnitudes of the masking stimuli were presented up to 30 dB SL (30 dB above the threshold level) in 3 dB steps.

In-channel masking functions were tested to confirm that a slope of unity was obtained with the current stimulus conditions (i.e. 16 Hz test and 16 Hz masker, 125 Hz test and 125 Hz masker). It was expected that both the test and the masking stimuli would be perceived by the same receptor if both stimuli were in the same range of frequency, so the masking function (slope of 1.0) would appear as the masker intensity increased. In-channel masking functions were tested with only five magnitudes of masking stimulus (i.e. 0, 3, 12, 21 and 30 dB SL), to reduce the testing time. One of six subjects completed the study with 3 dB steps of masker intensity in order to confirm that the expected slope had been obtained with those stimuli.

The subjects attended fourteen sessions (one subject attended two extra sessions to complete in-channel masking tests), each session lasted less than one hour. A single session consisted of one test stimulus with 10 sensation levels of masker (up to 30 dB SL). Within a single session, the frequency of the test and masking stimuli were always the same, except for in-channel masking conditions (i.e. 16 Hz test stimulus and 16 Hz masker, 125 Hz test stimulus and 125 Hz masker). Masking stimuli at different intensities were presented in a random order with the restriction that the session started with low intensity maskers and ended with high-intensity maskers. This order of presentation has been adopted by Gescheider *et al.*, (1983) in order to minimise any cumulative effects of adaptation. A summary of the stimulus conditions is shown in Table 11-1.

Table 11-1 Conditions of the test stimulus and the masking stimulus

Test stimulus	Masking stimulus	Intensity of masker
16 Hz sinusoidal	16 or 125 Hz centred 1/3 octave bandwidth vibration	0 - 30 dBSL (3 dB steps) above absolute thresholds of masker
31.5 Hz sinusoidal		
63 Hz sinusoidal		
125 Hz sinusoidal		

Unmasked thresholds (= absolute threshold of a test stimulus, without a masking stimulus) and masker thresholds (= absolute threshold of a masking stimulus) were also determined at the beginning of every session (before testing the masked thresholds). The order of applying the two contact conditions (i.e. finger and whole-hand conditions) and presenting the two masking stimuli (i.e. 16 and 125 Hz centred 1/3 octave bandwidth vibration) was balanced between the subjects. The order of presenting the four test stimuli (i.e. 16, 31.5, 63 and 125 Hz) was randomised between the sessions.

11.5.4 Threshold measurement conditions

Table 11-2 shows the psychophysical method employed for measuring the masked thresholds, unmasked thresholds and masker thresholds. All the thresholds were determined using two-interval two-alternative forced-choice (2IFC) tracking with the up-down method (three-down one-up rule) to yield a 79.4% correct response (see procedure details in Section 4.2.3, Method C).

Table 11-2 Masked threshold determination method

Method	Two-interval two-alternative forced-choice
Procedure	Staircase method (three-down one-up rule)
Duration of each observation	600 ms
Termination of a run	6 reversals

For the determination of unmasked stimulus thresholds and masker thresholds, several trials were presented, a trial consisted of the presentation of two stimuli, each 600 ms in duration, separated in duration by 600 ms. The subjects' task was to decide whether the first or the second period contained vibration stimuli.

For the masked thresholds, a 600 ms test stimulus was presented followed by a 600 ms pause followed by a 3000 ms masker stimulus; the masker stimulus contained a set of two observations, each 600 ms in duration, placed in the middle of the masker stimulus. The sequence of stimuli is illustrated in Figure 11-8. The duration of 600 ms was chosen for observation periods, the gap between the two observations, and masking duration before and after the onset of a test signal, because temporal summation of the Pacinian system is effective below about 500 ms (Gescheider *et al.*, 1978). A visual cue was provided by a light synchronised with the observation periods. For the masked threshold condition, a different type of light was provided for the period of a test stimulus and the period of an observation stimulus; the light blinked when presenting a test stimulus, and the light appeared continuously when presenting during an 'observation' period. Masked thresholds were determined with four test stimuli (i.e. 16, 31.5, 63 and 125 Hz) in conjunction with two masking stimuli (i.e. 16 and 125 Hz centred 1/3 octave bandwidth noise) at varying masker levels (from 0 to 30 dB SL) above the absolute threshold of the masker (see Table 11-1).

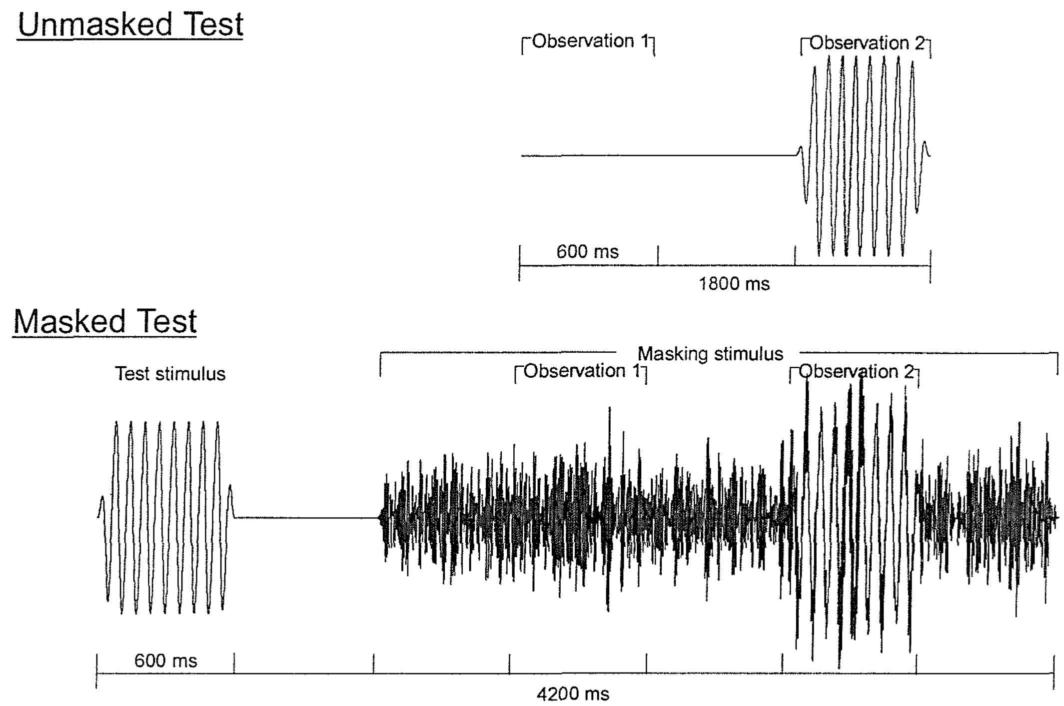


Figure 11-8 Stimulus timing of a 2IFC (two-interval forced-choice) trial for unmasked and the masked thresholds. The figure illustrates a test stimulus of 16 Hz with a masking stimulus of 125 Hz in which the stimulus occurred during the second stimulus observation.

11.5.5 Presentation of results

All thresholds were measured and expressed in acceleration (ms^{-2} r.m.s.); the amount of masking was presented in decibels, taking the unmasked threshold of each subject as a reference:

$$\text{Threshold shift (dB)} = 20 \cdot \log_{10}\left(\frac{A_f}{B_f}\right)$$

where A_f is the acceleration of the masked threshold, B_f is the acceleration of the unmasked threshold at the stimulus frequency, *f*.

For further analysis, the results were also converted into displacement using the equation:

$$\text{Displacement (in meters, peak)} = \frac{a_f}{(2\pi f)^2} \cdot \sqrt{2}$$

where a_f is the peak acceleration (ms^{-2} r.m.s.) measured at the stimulus frequency, *f*.

Note that the masked thresholds were determined by measuring sinusoidal vibration of test stimuli presented at the beginning of a trial, not including the 1/3 octave bandwidth stimuli.

11.6 RESULTS

11.6.1 Absolute thresholds

11.6.1.1 Unmasked thresholds

Throughout the 14 or 16 sessions, the unmasked thresholds (i.e. absolute thresholds of test stimuli with no masking vibration stimuli) for each test frequency were measured twice per subject. The two measured unmasked thresholds were not significantly different (Wilcoxon, $p>0.1$) at any test frequency. Individual threshold data averaged from two measurements for the two contact conditions are shown in Figure 11-9. It is seen that the whole hand condition significantly lowered absolute thresholds at all frequencies, by from 8.7 to 18.0 dB compared with the fingertip condition (Wilcoxon, $p<0.01$).

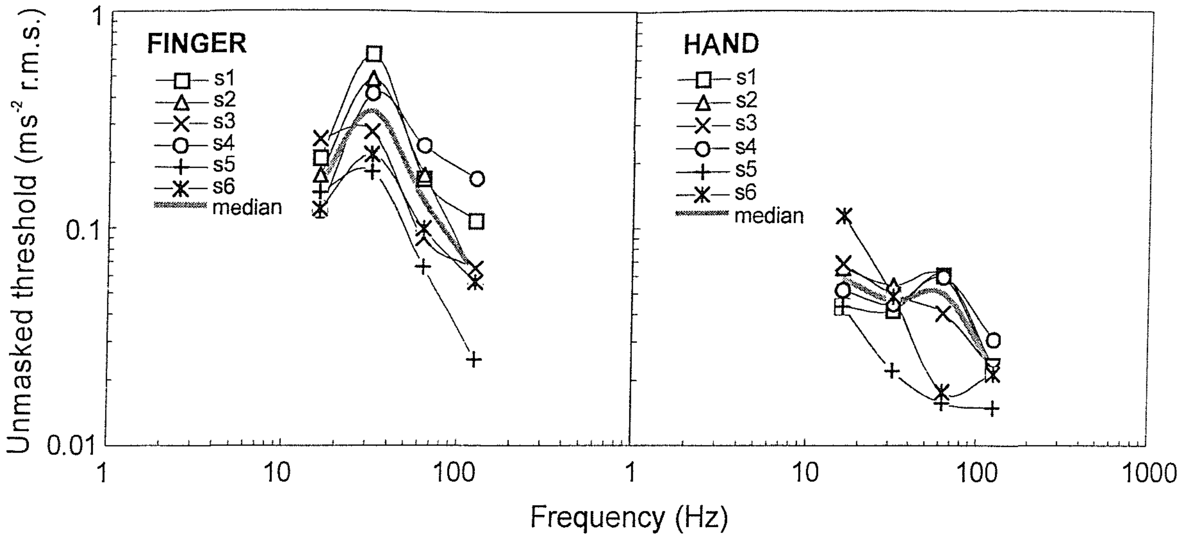


Figure 11-9 Individual unmasked thresholds obtained at the fingertip and the whole hand. The data shown for each of six subjects (s1 to s6) are the average of two unmasked thresholds for each subject.

Analysis of variance (tests of within-subjects effects) showed that the unmasked thresholds were dependent of stimulus frequency and contact position (p>0.01) with no effect of repeated measurement (p>0.9). The results indicate that the unmasked thresholds determined with the same condition were reasonably repeatable.

Median unmasked thresholds for the six subjects determined with the finger and the whole hand conditions are expressed in acceleration and peak displacement and are presented in Figure 11-10. Both threshold contours were similar to the thresholds determined in the previous studies with the same contact conditions and measurement methods (see Figure 11-5).

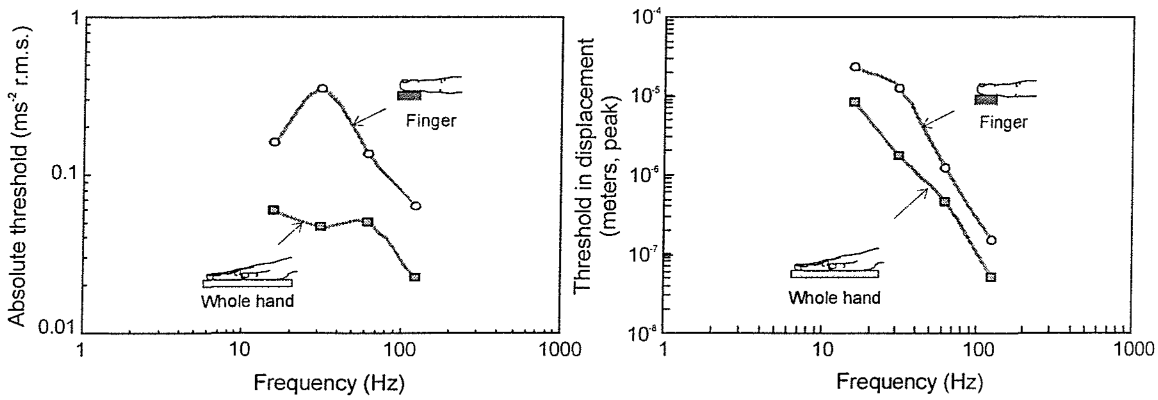


Figure 11-10 Median absolute thresholds (unmasked thresholds) at the finger and the whole hand. Data expressed in acceleration and displacement

11.6.1.2 Threshold of masker

The thresholds of two maskers (i.e. 16 Hz and 125 Hz centred 1/3 octave bandwidth vibration) were obtained four times for each contact condition. According to the analysis of variance, the measured thresholds had no dependence on repeated measurement ($p>1.0$) but depended on measured frequency and contact condition ($p<0.01$).

11.6.1.3 Sinusoidal versus 1/3 octave bandwidth vibration stimuli

It was thought that the absolute thresholds determined by the two different waveforms of the vibration stimuli (i.e. sinusoidal and 1/3 octave bandwidth vibration) might affect the absolute threshold value. The averaged absolute thresholds determined with the masker stimuli (at 16 Hz and 125 Hz with 1/3 octave bandwidth vibration) and the unmasked sinusoidal stimuli (at 16 Hz and 125 Hz) from each subject were compared for both the finger and the whole hand conditions and are presented in Figure 11-11. No significant difference in threshold was found between the two vibration waveforms, sinusoidal or 1/3 octave vibration (Wilcoxon, $p>0.1$).

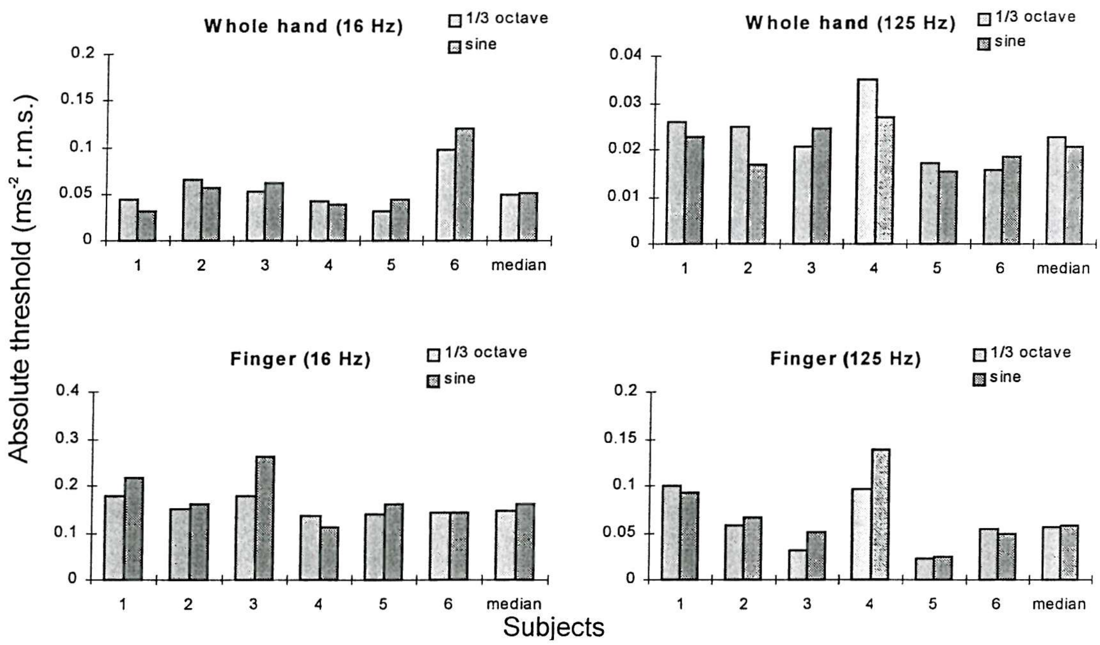


Figure 11-11 Thresholds for 1/3-octave bandwidth vibration and sinusoidal vibration: comparison of the averaged absolute thresholds between 'threshold of masker' and 'unmasked threshold' within each subject.

11.6.2 Masked thresholds

11.6.2.1 Threshold shifts caused by increased levels of masker

The first approach to analysis was to see the overall patterns of the masking functions within each of the six subjects. Threshold shifts (in dB) were calculated (see Section 11.5.5) from the measured thresholds and were scattered over the graphs showing threshold shifts (in dB) versus the sensation level of the masker (in dB SL), which are presented for each measurement frequency in Figure 11-12.

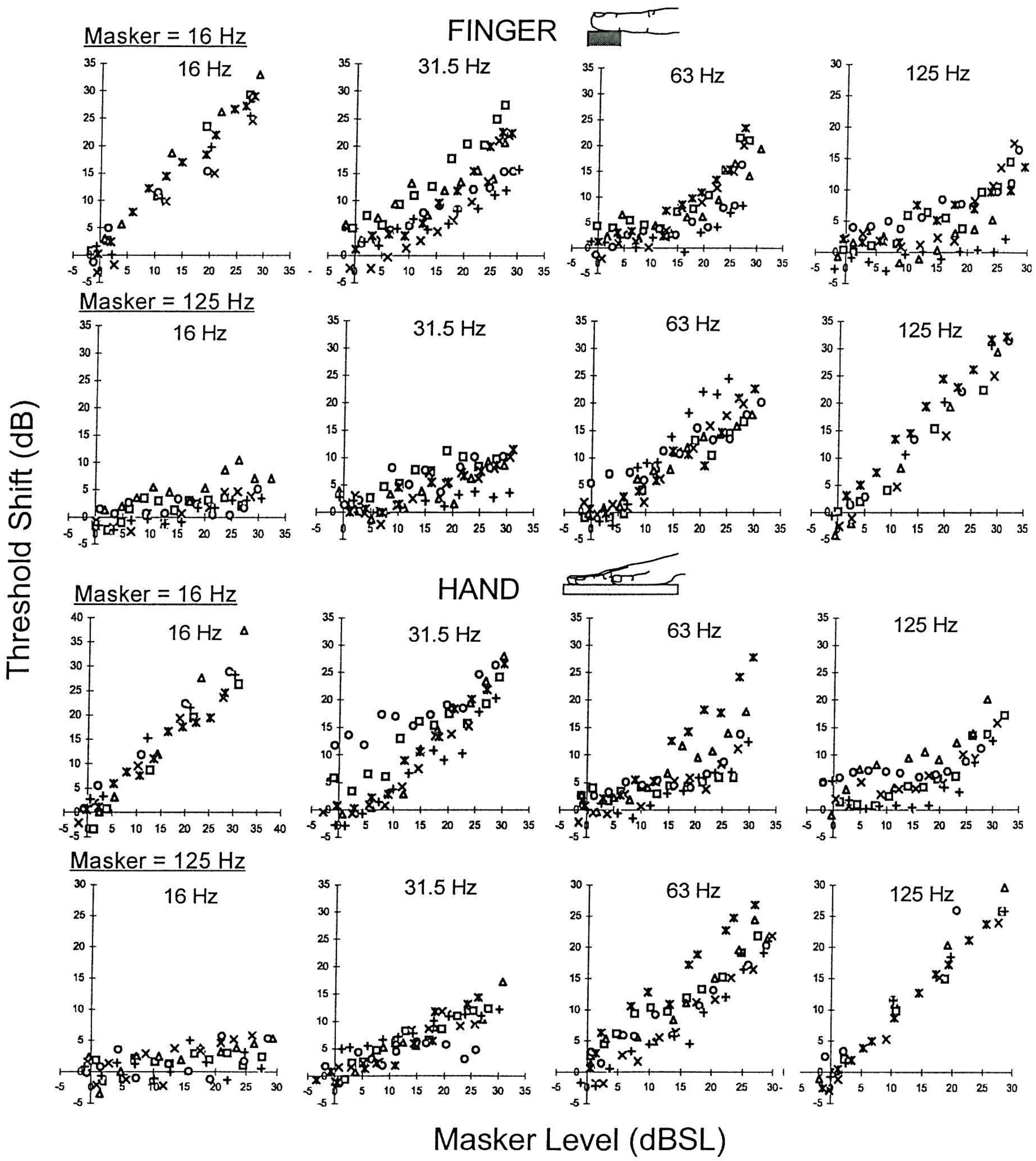


Figure 11-12 Threshold shifts (in dB) for six subjects scattered as a function of the intensity of sensation level of the masker (in dB SL).

Within-channel masking

Looking at the conditions for testing within-channel masking functions in Figure 11-12 (i.e. 125 Hz masker with 125 Hz test stimulus, 16 Hz masker with 16 Hz test stimulus), the masked thresholds increased linearly, with a slope of almost 1.0; thresholds shifted upwards by the amount of the increment of the masker). It is evident that the 1/3-octave vibration stimuli masked the detection of the sinusoidal stimuli, showing that both stimuli were mediated by the same receptor.

Cross-channel masking

For the other masking conditions presented in Figure 11-12, they are roughly seen as similar to the cross-channel masking functions, containing both horizontal lines and 45 degree slopes. Cross-channel system masking is based on the assumption that Pacinian and non-Pacinian systems are independent; a masker selectively stimulating one system should not alter the detectability of a signal in the other system (Labs *et al.,* 1978; Hamer, 1979; Hamer *et al.*, 1983 Gescheider, 1982; Verrillo *et al.*, 1983). A horizontal line in the masking function indicates an independence of the detection response, as indicated by Hamer *et al.* (1983): a Pacinian system masker should not affect signal detectability within the non-Pacinian system, or vice-versa.

Further observation of individual data in Figure 11-12, made it clear that the results reflected the triplex model rather than the duplex model, because:

- Some of the individual data contain more than one horizontal line, indicating more than two receptors were involved in the response.
- With a particular condition (16 Hz test with 125 Hz masker), masking did not occur, showing a horizontal line for all levels of the masker. A slope should appear if masking has been seen with other test frequencies with the same masker.

These observations suggested that another independent response was involved in the detection of the vibration stimuli and could be identified from the masking threshold results. Predictions of cross-channel masking functions were therefore made from the triplex model for further analysis.

11.7 PREDICTION OF MASKING FUNCTIONS FROM THE TRIPLEX MODEL

It was assumed that there were Pacinian receptors and two non-Pacinian receptors involved in the detection of hand-transmitted vibration. Each receptor should be independent: when a masker selectively stimulates a particular receptor it will not affect detection by another receptor it does not stimulate.

11.7.1 Alternative Triplex models

It appeared that predictions of cross-channel masking functions needed to be derived from the triplex model. However, it is not known whether NP II is capable of spatial summation (Bolanowski, *et al.*, 1988). It is therefore uncertain whether the sensitivity of non-Pacinian receptors changes when vibration is applied to the fingertip or to the whole hand. The triplex model was proposed with differing threshold frequency functions for the NP II receptor, as shown in Figure 11-13. All the alternatives consisted of three threshold frequency functions, the P functions with a U-shaped curve having a slope of –12 dB per octave at frequencies below 200 Hz, the NP I functions with a horizontal line, the NP II functions with a linear slope. The shapes of the three receptor functions originated from the triplex model proposed by Gescheider *et al.* (1985).

According to each of these models, the initial thresholds for 125 Hz stimuli were mediated by Pacinian receptors, whereas the thresholds at low frequency (i.e. 16 and 31.5 Hz) were mediated by either NP I or NP II receptors, depending on the triplex model being applied. This implies that the masker stimulus at 125 Hz should first excite the P receptor with all of the models, but the masker stimulus at 16 Hz would first excite either NP I or NP II receptors.

11.7.2 Schematic prediction of masking functions

Predictions of cross-system masking functions from each of three alternative triplex models are illustrated in Figure 11-14 and Figure 11-15. It is seen that masking functions are not identical for the three alternative triplex models, as the intersections between the three receptors change when altering the NP II thresholds. No response from the NP II is obtained by Triplex model 1, because the masker will always reach the threshold of NP II before the test stimuli reach this threshold.

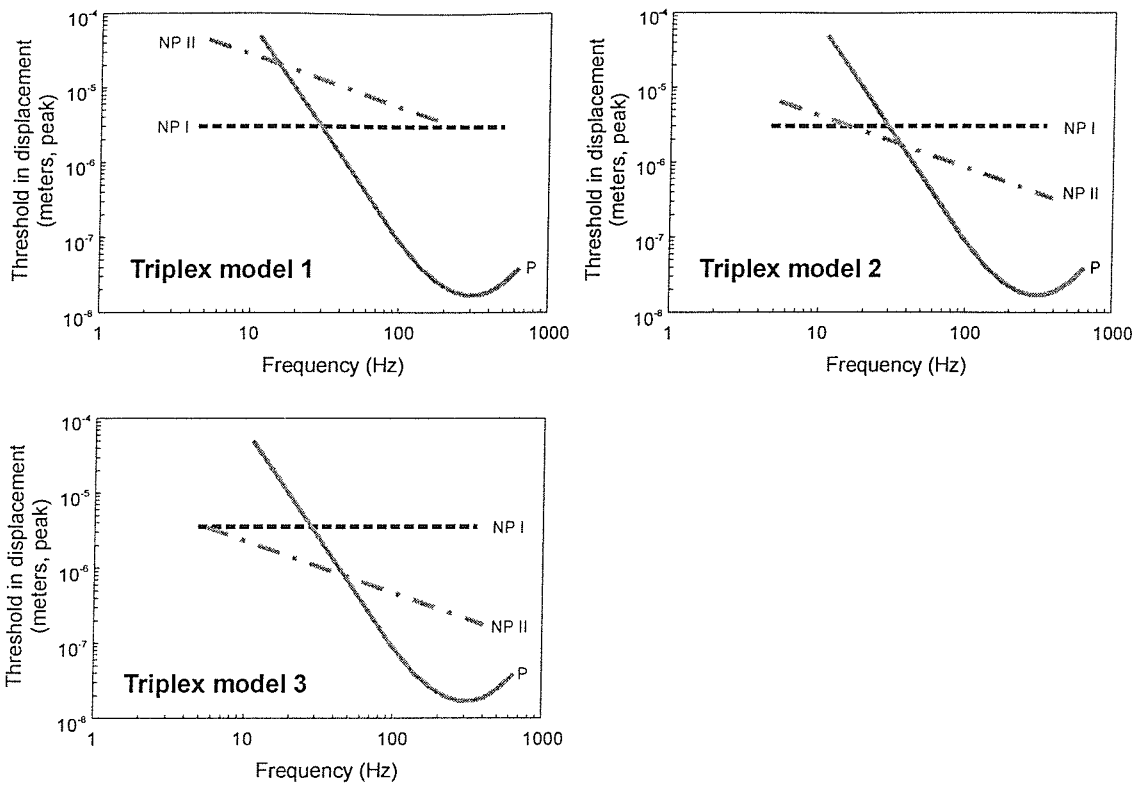


Figure 11-13 Schematic presentation of alternative triplex models for the detection of hand-transmitted vibration, consisting of threshold frequency functions of three independent receptors (i.e. P, NP I and NP II). (Note that the displacement levels do not necessarily correspond to the receptor thresholds.)

It was expected that the frequency response of each receptor might not look like exactly as assumed in the triplex model in Figure 11-13 (e.g. having straight lines for non-Pacinian receptors, a U-shape for Pacinian receptors). The predictions did not include the effect of the contact conditions, which differ between the finger and whole hand contact. It is also possible that each subject has a different sensitivity to the three receptors; one subject could have a sensitive non-Pacinian receptor and an insensitive Pacinian receptor, or vice versa. The measured masking functions were therefore not necessarily expected to be identical to the predicted masking functions.

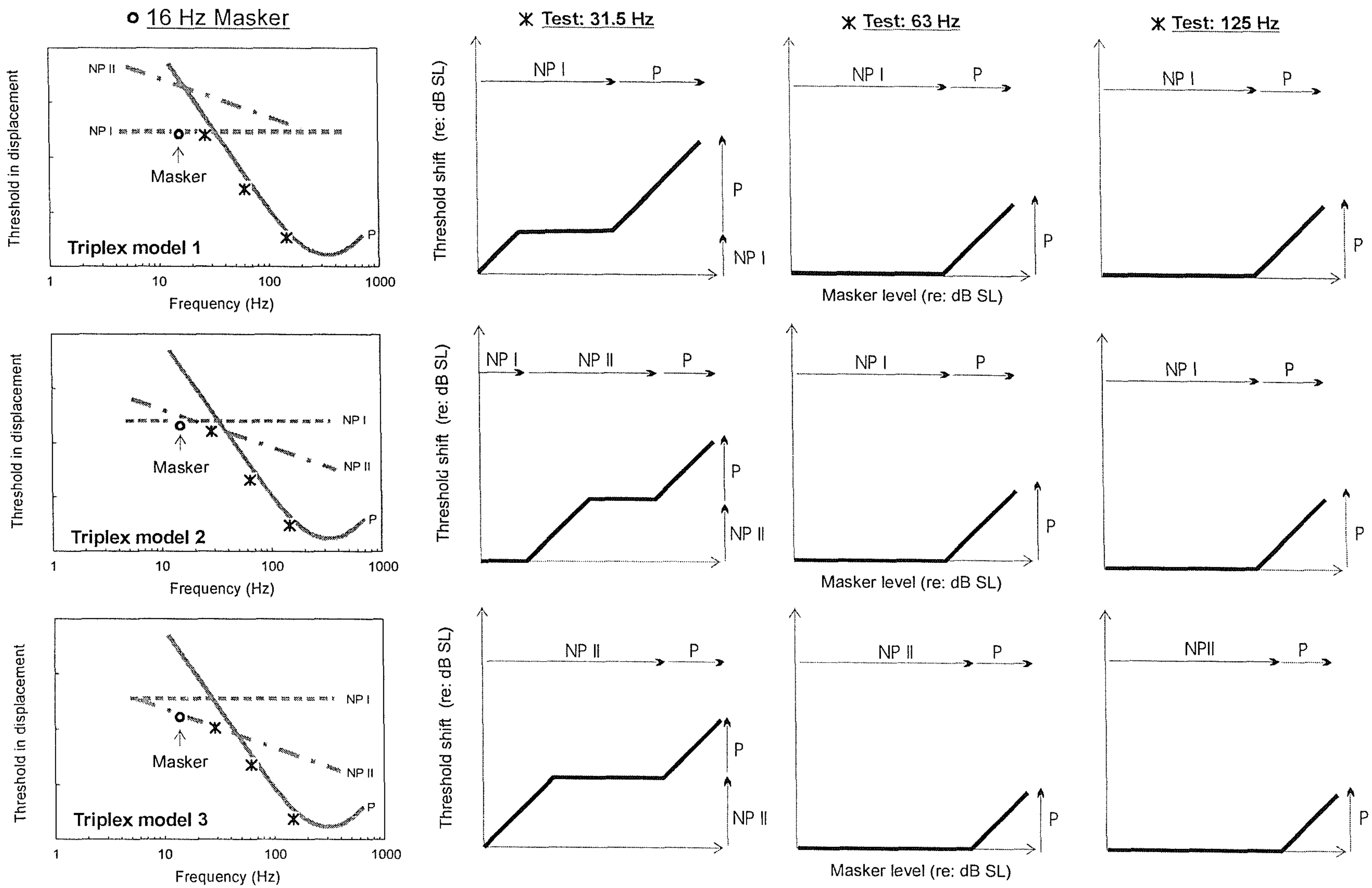


Figure 11-14 Schematic prediction of cross-system masking functions for 16 Hz masker from three alternative triplex models according to the procedure shown in Figure 11-13 .

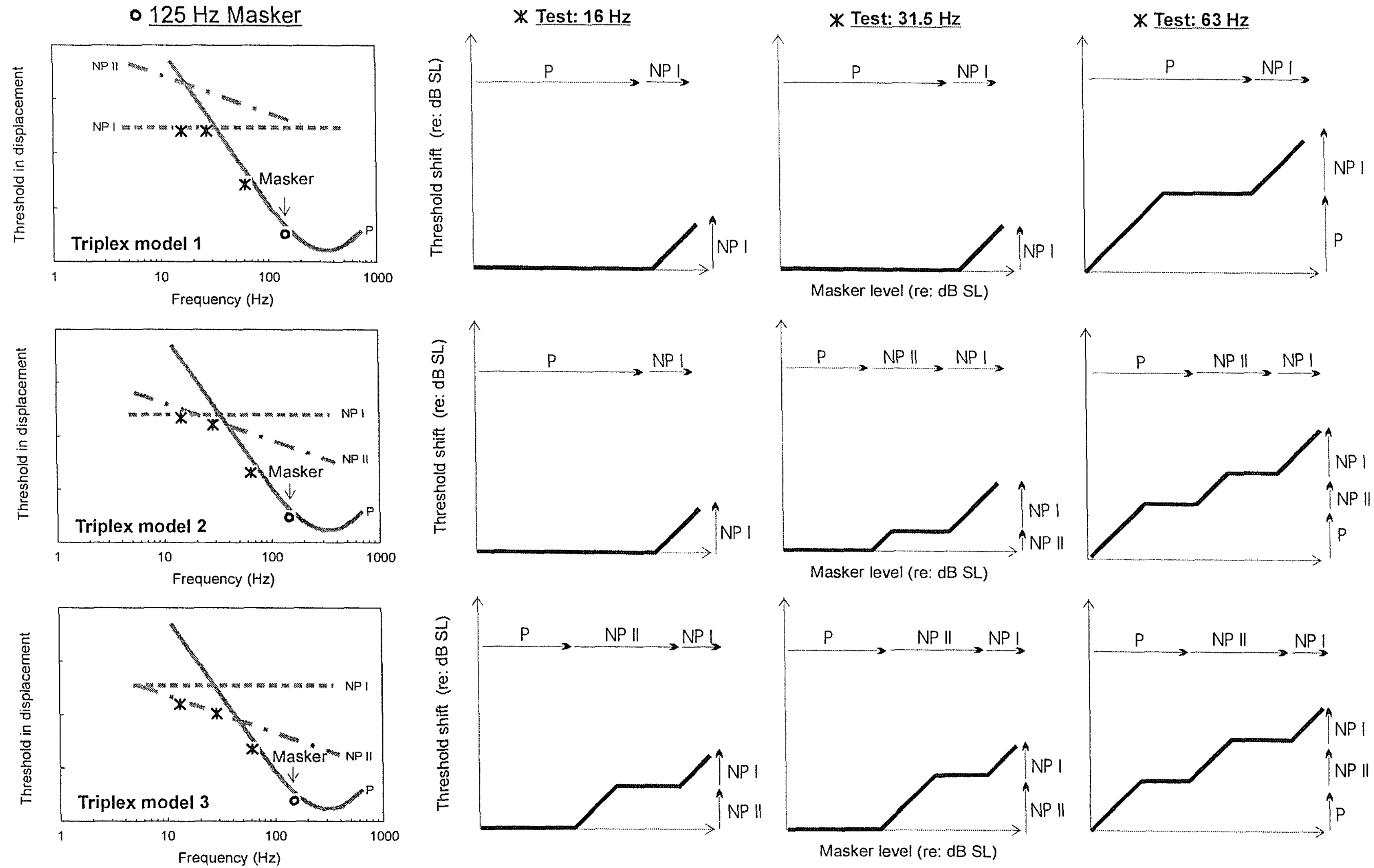


Figure 11-15 Schematic prediction of cross-system masking functions for 125 Hz masker from three alternative triplex models according to the procedure shown in Figure 11-13.

11.7.3 Procedure for determining thresholds of independent receptors

It was thought that the analysis of measured masked thresholds should be performed individually rather than taking an average of results for the six subjects, so that intersections of the receptors could be observed for each subject. Determinations of thresholds for individual receptors were carried out with the following procedure:

1. Re-plot the masked threshold empirical data for each test frequency in decibels (reference 10^{-6} ms^{-2} r.m.s.) of acceleration.
2. Fit lines over the data points, with the lines strictly either horizontal or with a slope of 1.0.
3. Estimate the thresholds of each receptor from the masking function graphs and mark over the graph a function of frequency.
4. Compare the estimated thresholds for each receptor obtained between the two maskers (16 and 125 Hz), check whether they are consistent throughout the measurements.
5. Combine the marked data for 16 Hz and 125 Hz maskers. Re-scale into displacement and produce the threshold contour for each receptor.
6. Compare the threshold contours of the six subjects to see the variation in thresholds between the subjects.

11.7.4 Determination of receptor thresholds from empirical masked thresholds

Following the procedure identified in Section 11.7.3, masked threshold data were re-plotted and analysed for individual subjects. The analysis was based on the assumption that a 125 Hz masker is initially mediated by Pacinian receptors so any horizontal lines were assumed to be caused by mediation of non-Pacinian receptors. Due to the difficulty in separately identifying the non-Pacinian receptors corresponding to NP I and NP II, they are temporary labelled as NPa and NPb.

All the results are illustrated for individual subjects, and shown separately for the two contact conditions: in Figure 11-16 through Figure 11-21 for the finger condition, in Figure 11-22 through Figure 11-27 for the whole hand condition.

The data for most of the cross-channel masking functions, showed one or two horizontal lines within the range of masker magnitudes (from 0 to 30 dB SL), indicating combined responses from up to three receptors. However, the characteristics of the masking functions varied between the subjects and the test conditions.

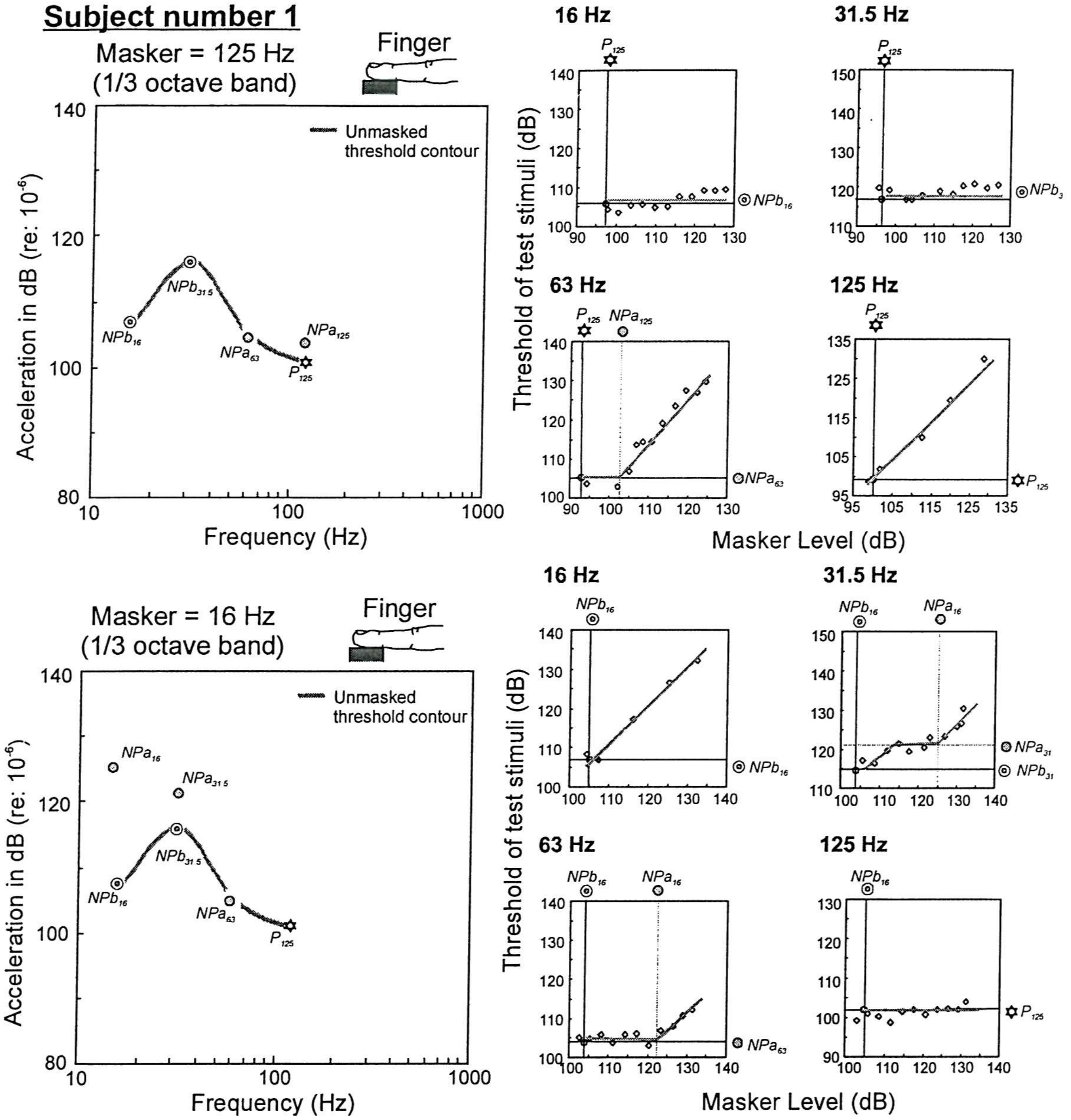


Figure 11-16 Masked thresholds determined with the finger condition for Subject 1: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as *P*) and two non-Pacinian (displayed as *NPa*, *NPb*) receptors.

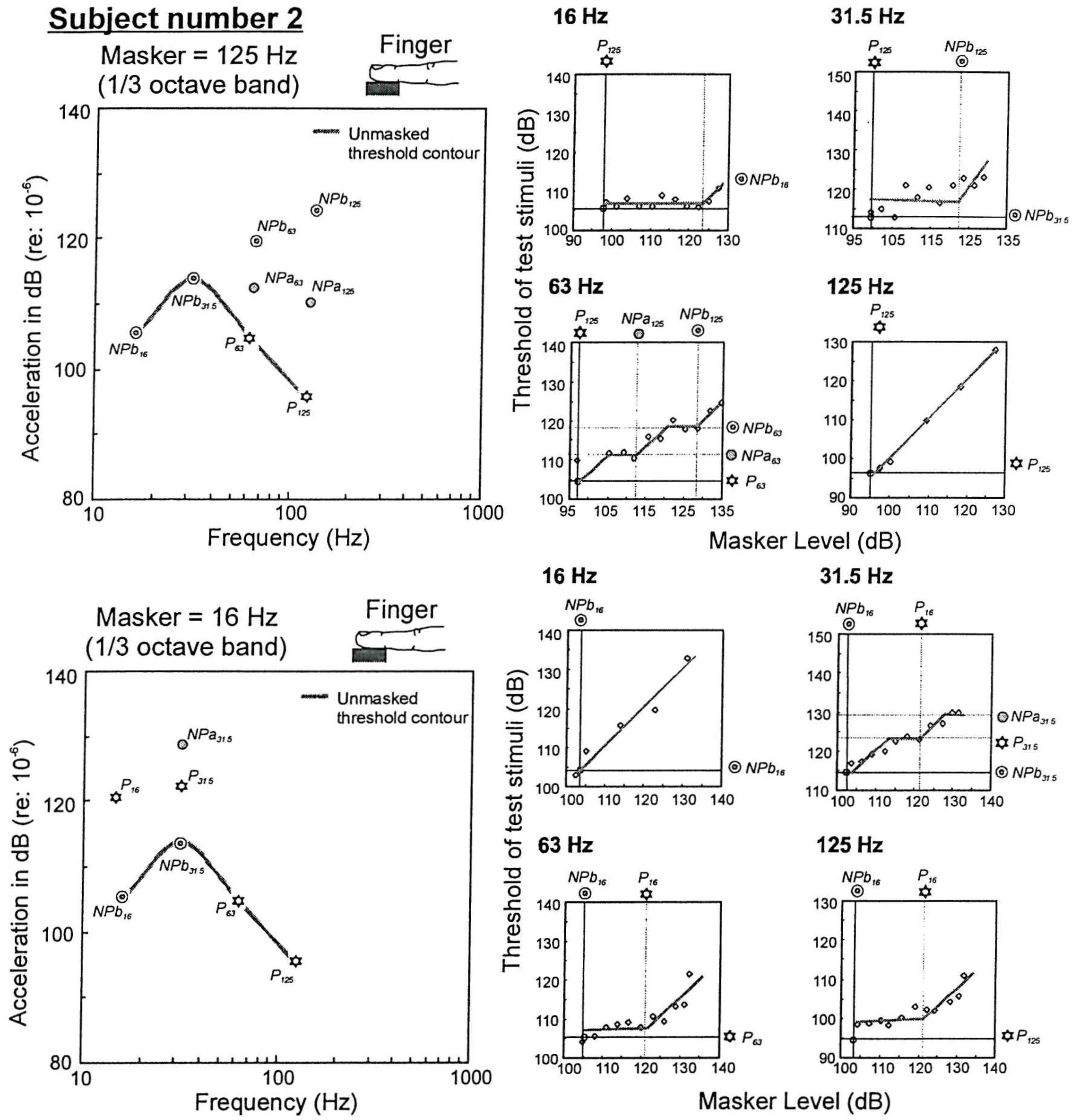


Figure 11-17 Masked thresholds determined with the finger condition for Subject 2: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as *P*) and two non-Pacinian (displayed as *NPa*, *NPb*) receptors.

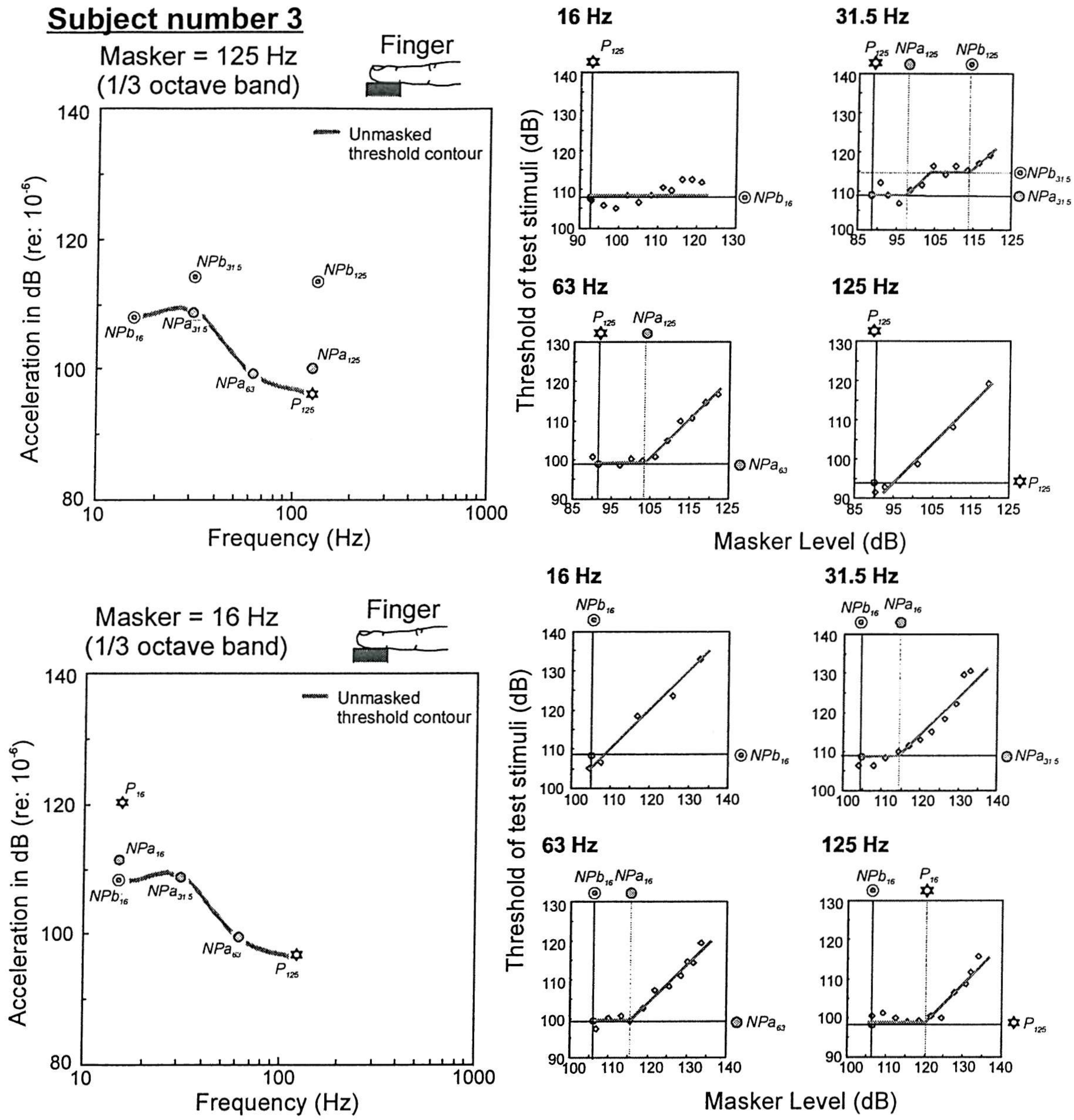


Figure 11-18 Masked thresholds determined with the finger condition for Subject 3: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as *P*) and two non-Pacinian (displayed as *NPa*, *NPb*) receptors.

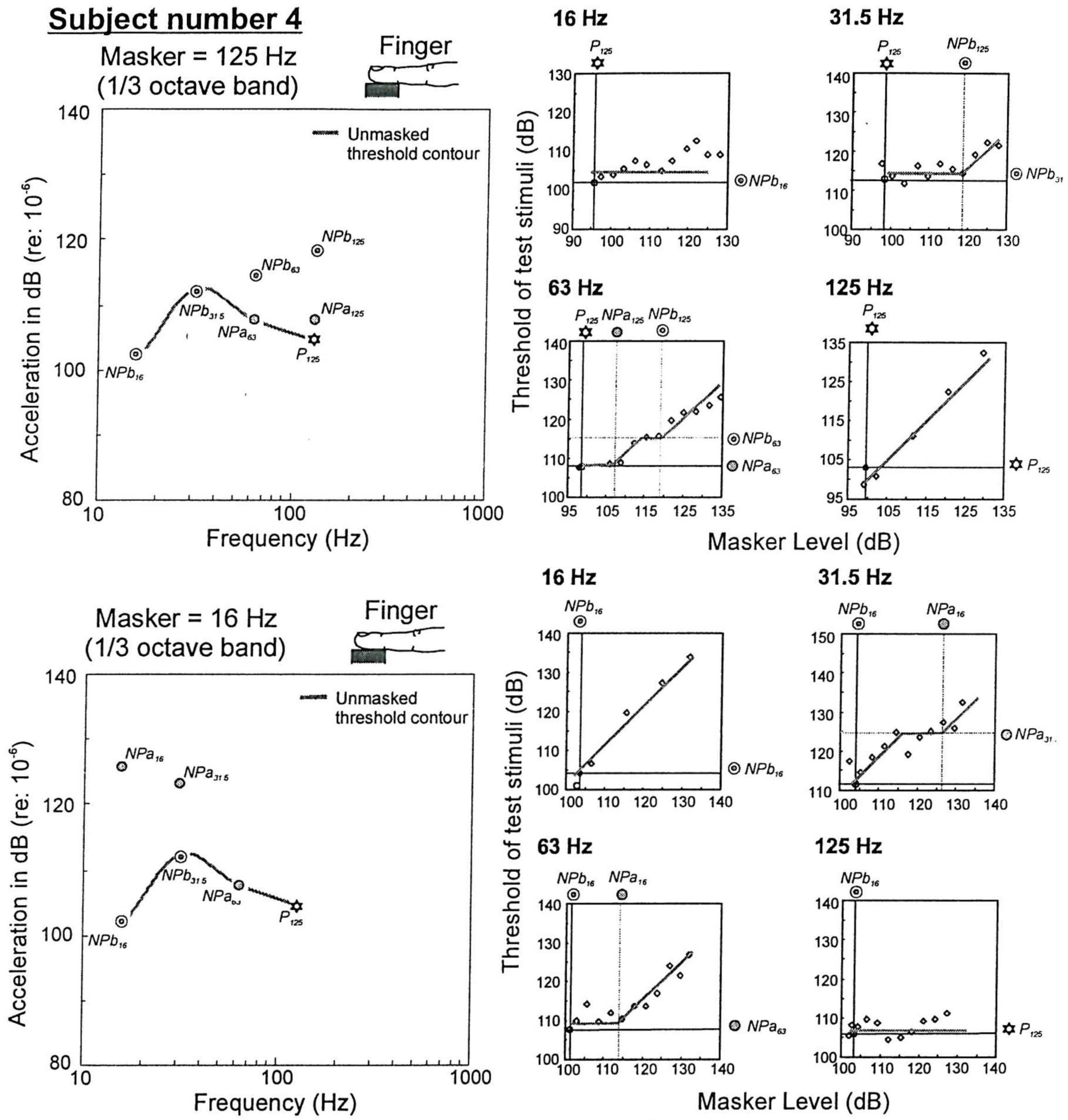


Figure 11-19 Masked thresholds determined with the finger condition for Subject 4: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as *P*) and two non-Pacinian (displayed as *NPa*, *NPb*) receptors.

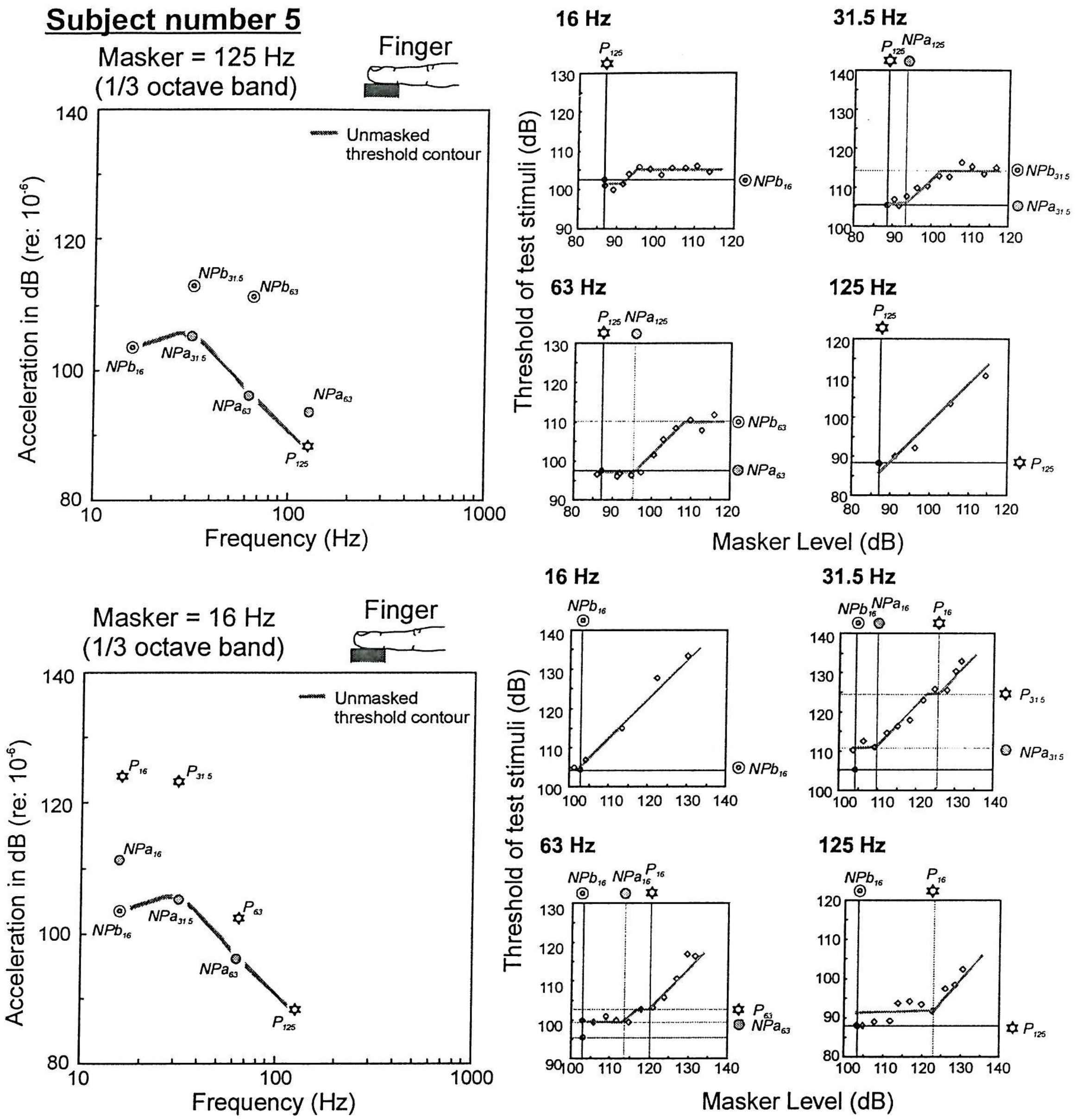


Figure 11-20 Masked thresholds determined with the finger condition for Subject 5: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as *P*) and two non-Pacinian (displayed as *NPa*, *NPb*) receptors.

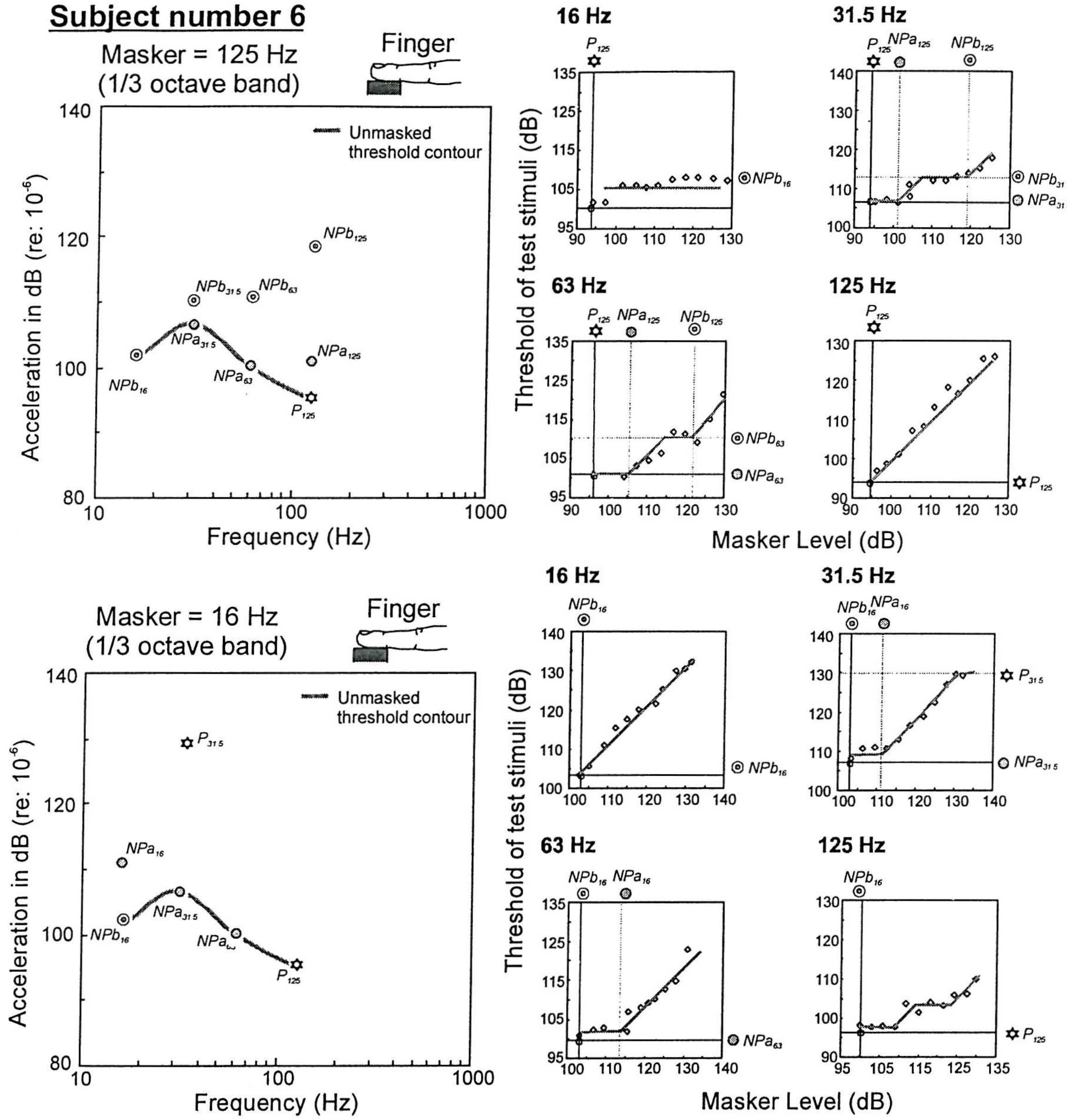


Figure 11-21 Masked thresholds determined with the finger condition for Subject 6: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as *P*) and two non-Pacinian (displayed as *NPa*, *NPb*) receptors.

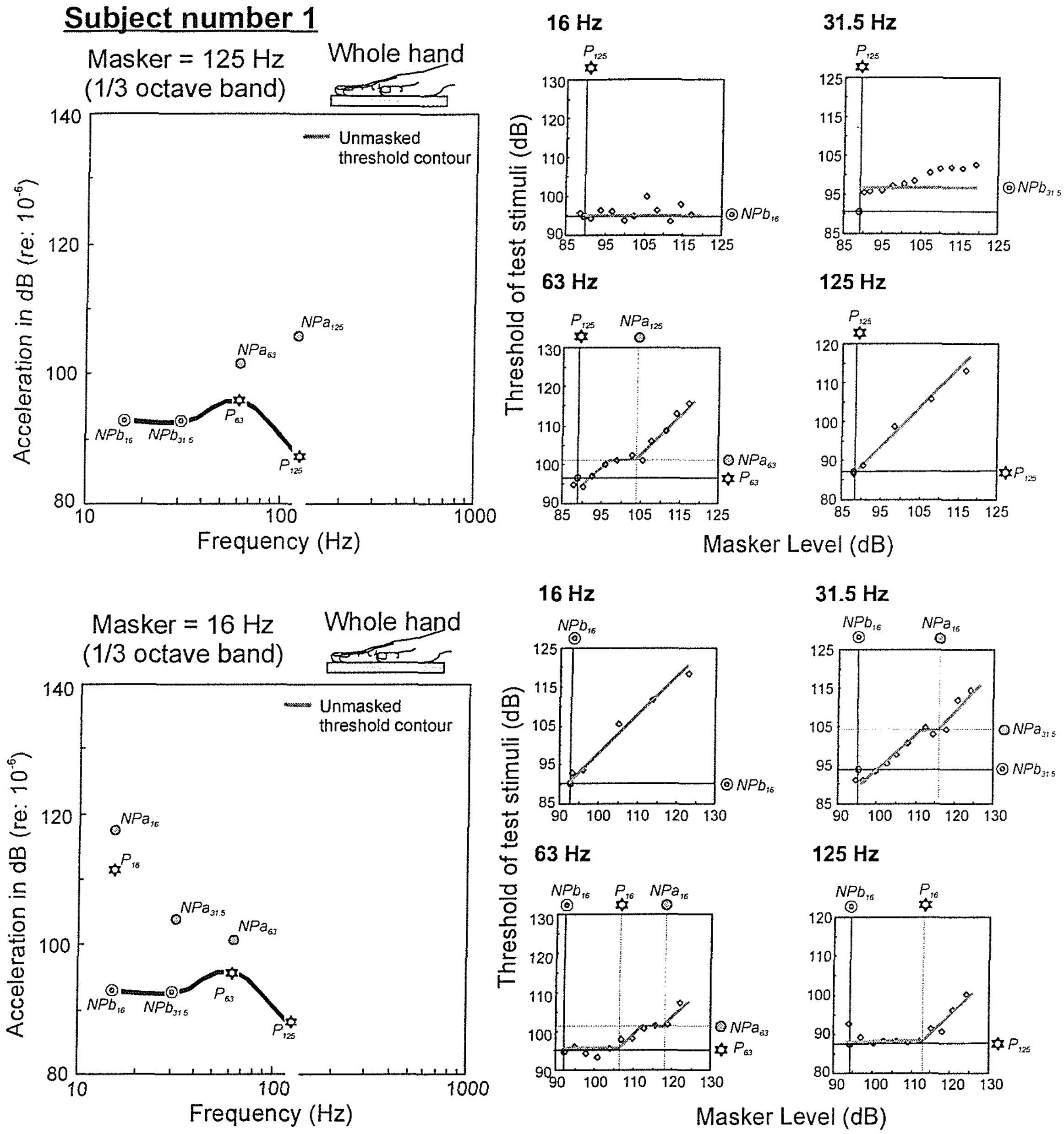


Figure 11-22 Masked thresholds determined with the whole hand condition for Subject 1: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as *P*) and two non-Pacinian (displayed as *NPa*, *NPb*) receptors.

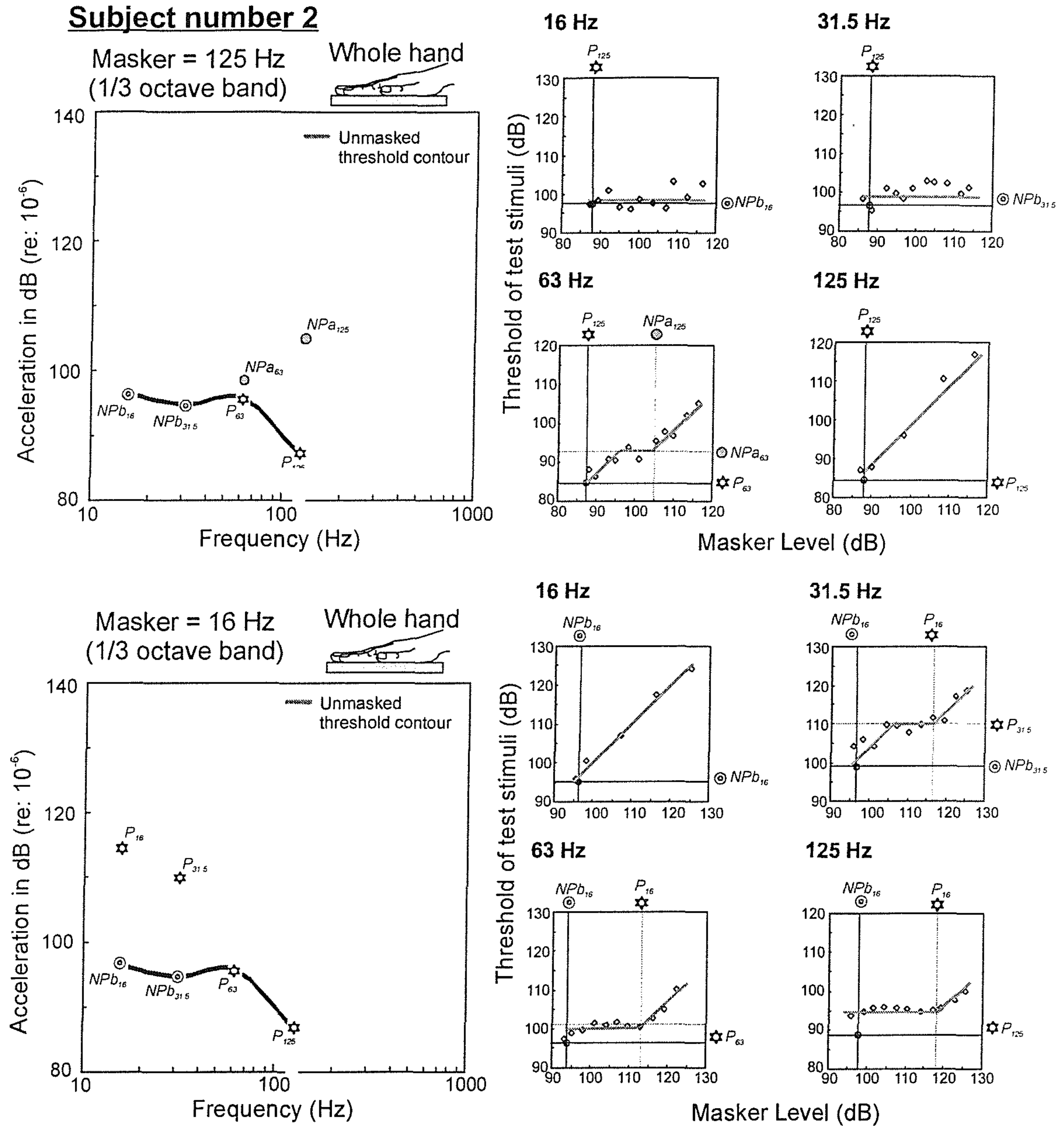


Figure 11-23 Masked thresholds determined with the whole hand condition for Subject 2: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as *P*) and two non-Pacinian (displayed as *NPa*, *NPb*) receptors.

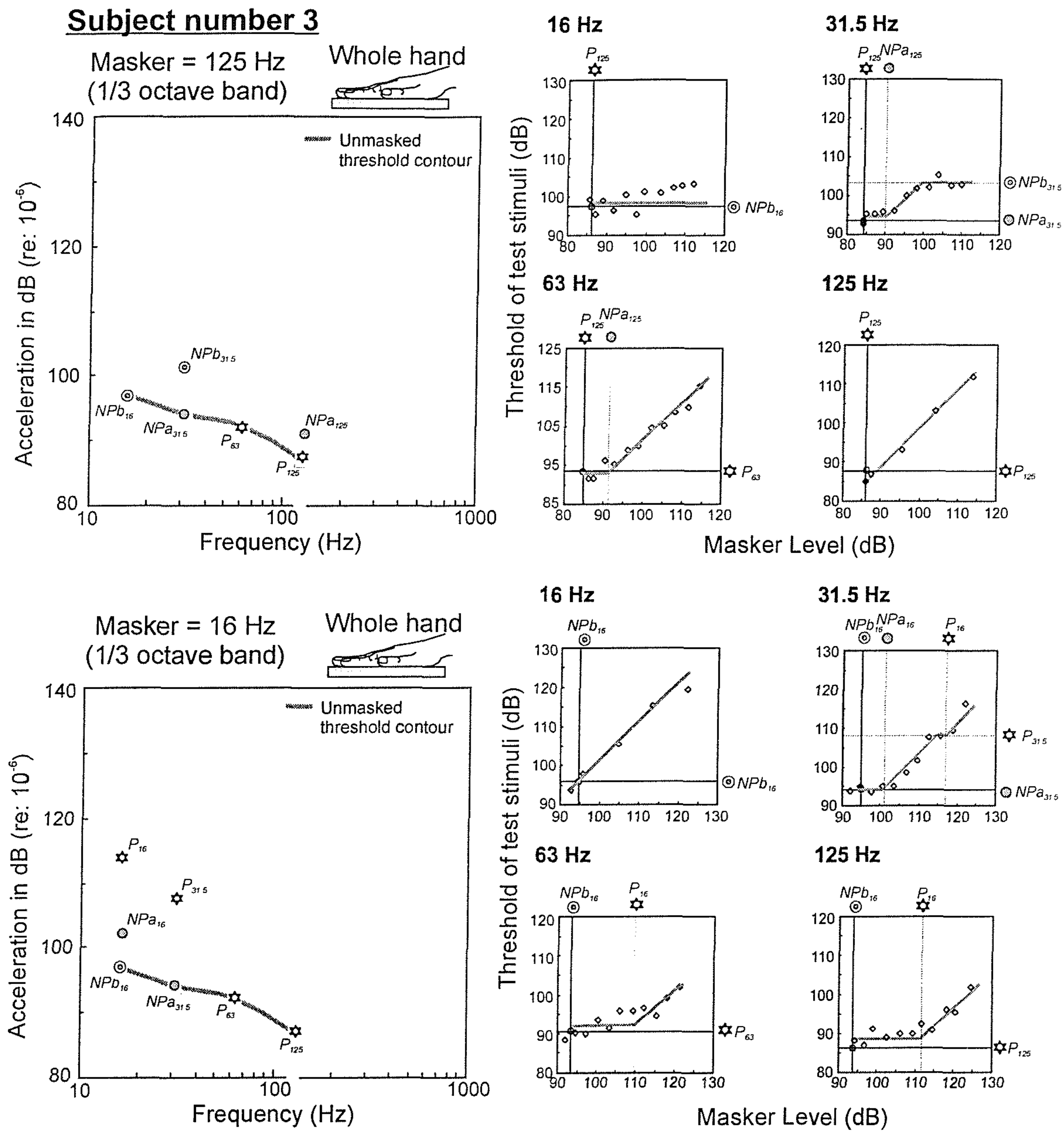


Figure 11-24 Masked thresholds determined with the whole hand condition for Subject 3: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as *P*) and two non-Pacinian (displayed as *NPa*, *NPb*) receptors.

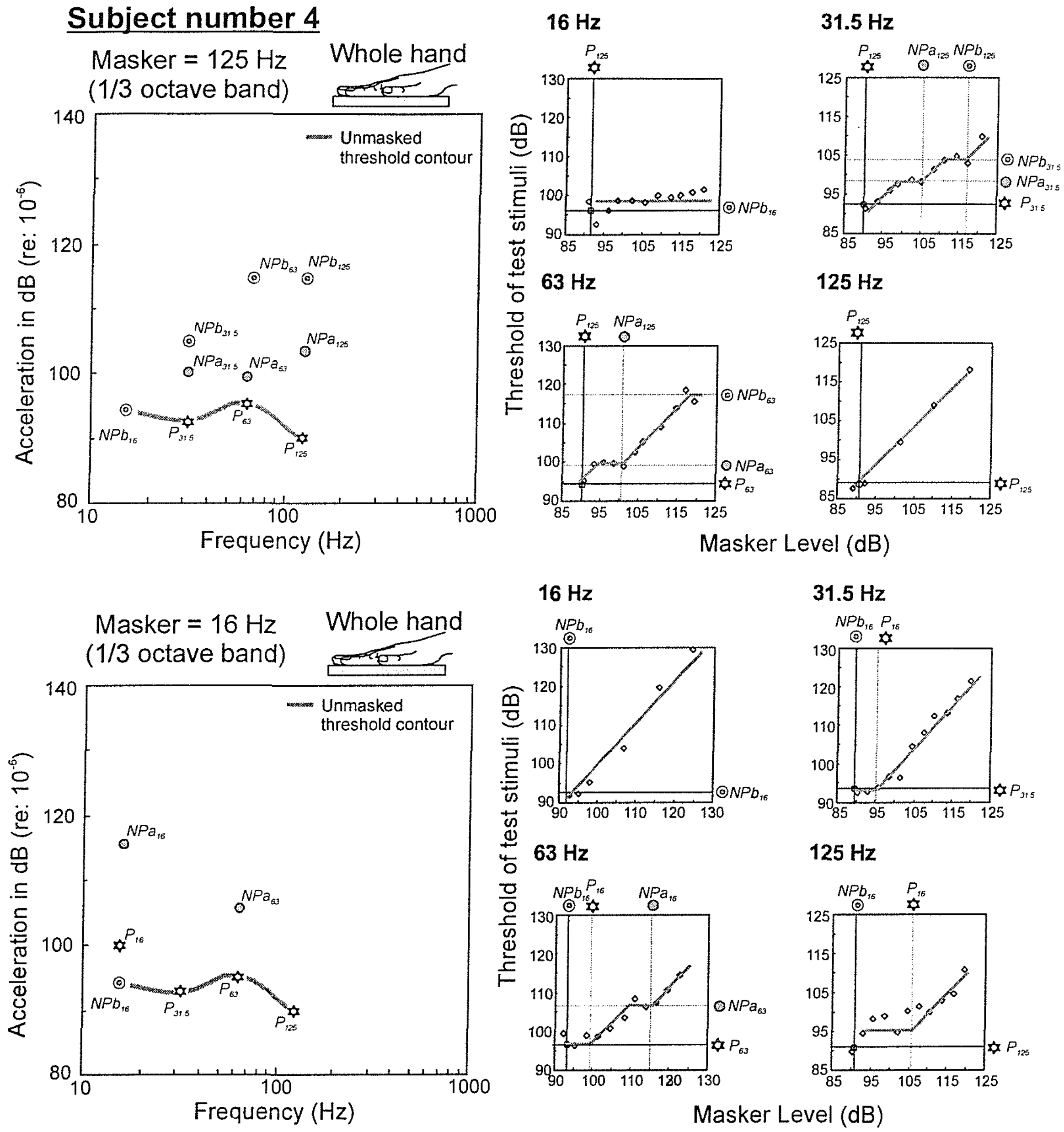


Figure 11-25 Masked thresholds determined with the whole hand condition for Subject 4: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as *P*) and two non-Pacinian (displayed as *NPa*, *NPb*) receptors.

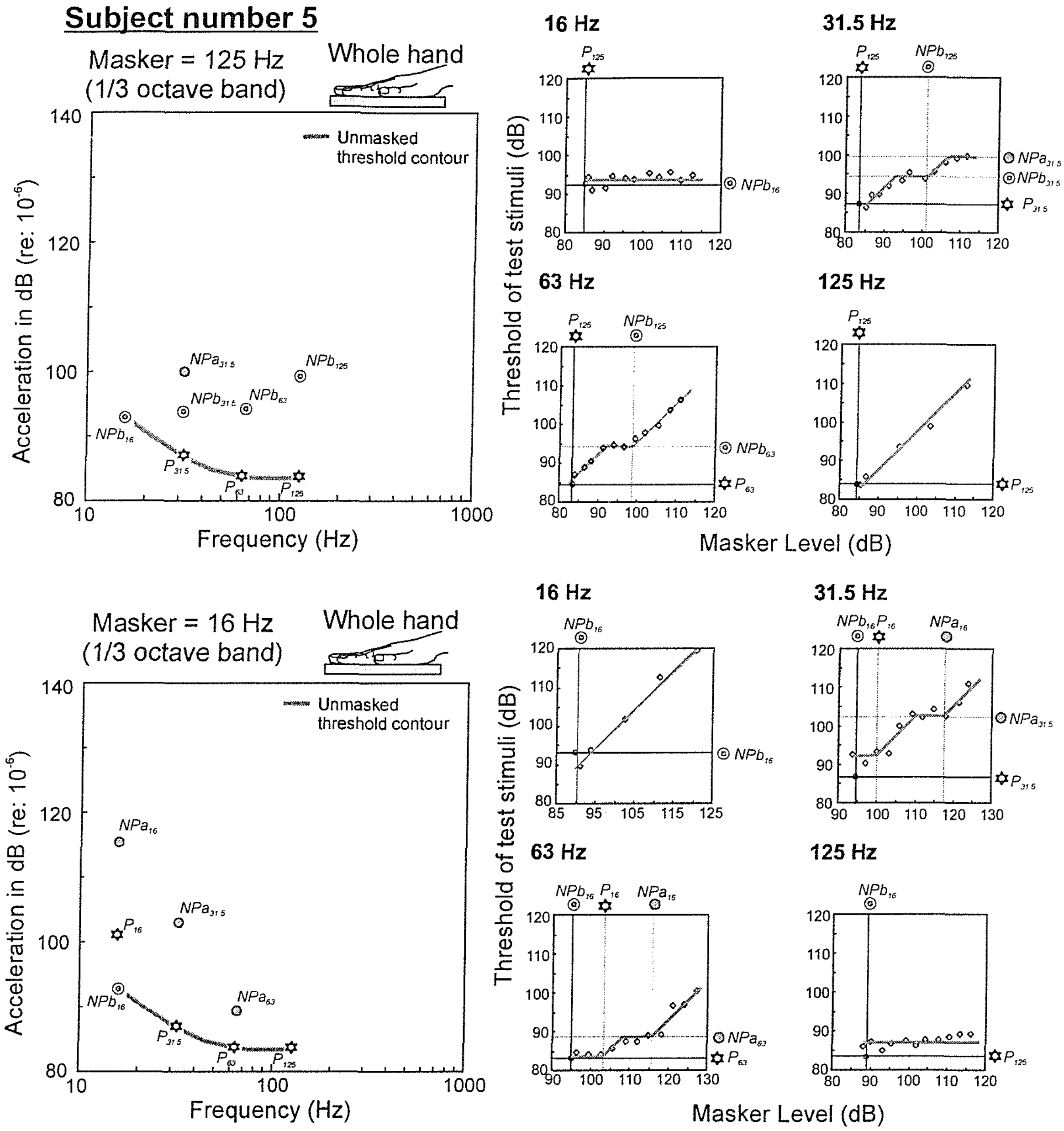


Figure 11-26 *Masked thresholds determined with the whole hand condition for Subject 5: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as P) and two non-Pacinian (displayed as NPa, NPb) receptors.*

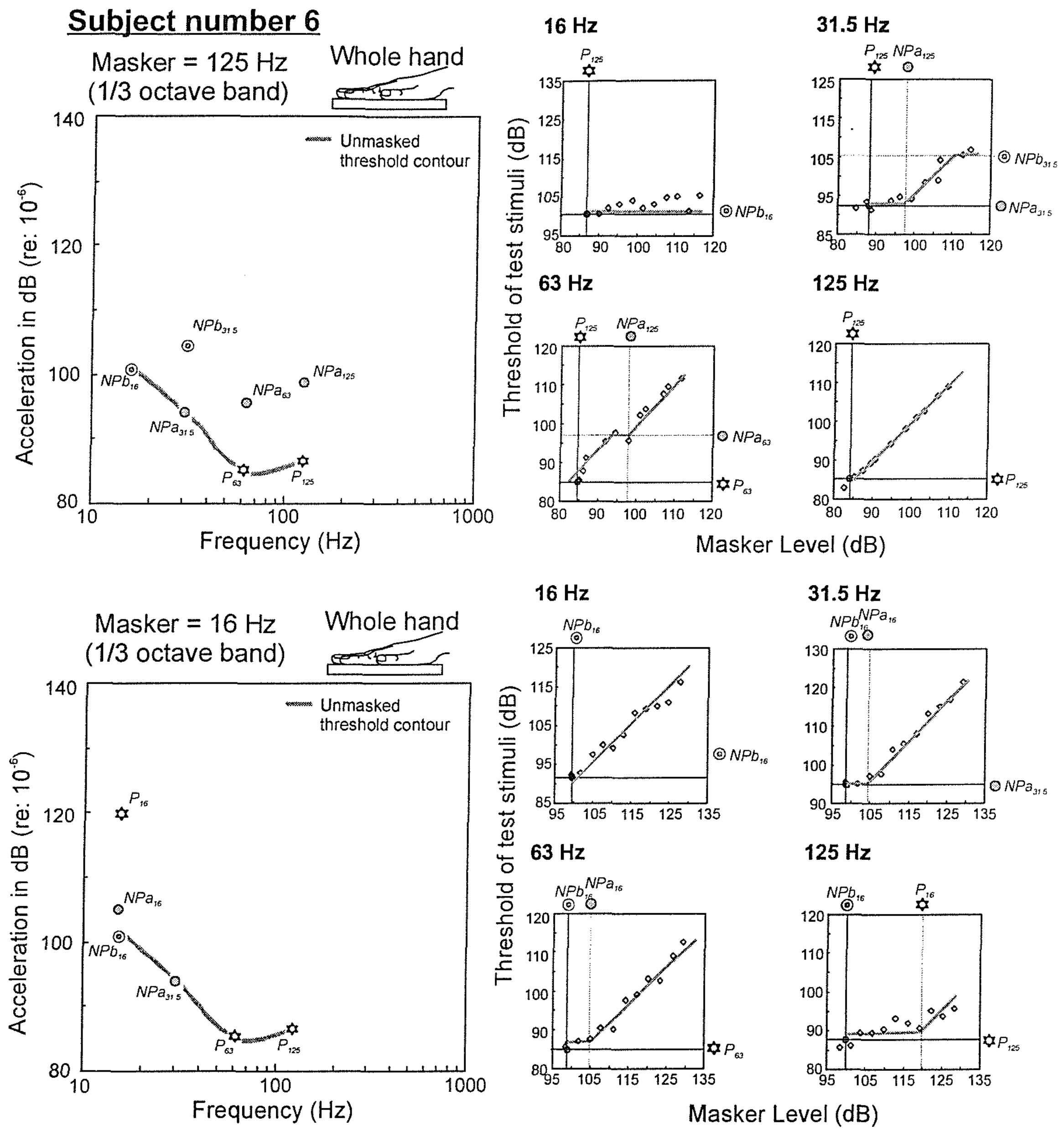


Figure 11-27 Masked thresholds determined with the whole hand condition for Subject 6: grey lines (strictly formed from either horizontal lines or a slope with gradient 1.0) representing masking functions to estimate thresholds of Pacinian (displayed as *P*) and two non-Pacinian (displayed as *NPa*, *NPb*) receptors.

11.8 DISCUSSION

11.8.1 Within-channel masking function

Within-channel masking was observed in the results with the same frequency of test and masking stimuli (i.e. 16 Hz and 125 Hz). Lines with a slope of 1.0 were virtually identical for both low frequency and high frequency maskers. Within-channel masking functions have been examined in several masking experiments with vibrotactile stimuli (Verrillo and Capraro, 1975; Hamer *et al.*, 1983) and also with auditory stimuli within a critical band (e.g., Hawkins and Stevens, 1950). These studies also observed masking functions with a slope of 1.0 above about 10 dB SL, while displaying a substantial amount of negative masking at low masker levels (below about 10 dB SL). Due to the limited design of within-channel masking tests in the present study (tested with 0, 3, 15 and 30 dB SL), particularly at low levels of masker, the negative masking phenomenon was not clearly displayed.

The negative masking phenomenon is possibly dependent on the type of masking stimulus. Hamer *et al.* (1983) found that the negative masking effect was more extensive when using a sinusoidal masker than when using a random noise masker. Green (1960) investigated signal detectability using auditory stimuli and reported that the detection of sinusoidal signals in noise is improved if the signal is presented as an in-phase addition to a background sinusoid of the same frequency. In effect, the observer finds easier to note the difference in amplitude of a sinusoid between the signal alone and the signal plus background signals. Rabb *et al.* (1963) found that the negative masking effect depended on stimulus duration, which suggests that the difference between the signal and the noise were detected by energy changes.

11.8.2 Cross-channel masking function

Cross-channel masking functions were observed in the results of *all* subjects, some showed two horizontal lines indicating the response of a third receptor channel. The threshold contours for the three-receptor channels were assembled from the six subjects and are shown in Figure 11-28 with separate illustrations for each receptor channel for each of the six subjects. The results provided mean values and give rough indications of the threshold contours for individual receptor channels. It should be noted that at some frequencies the thresholds in Figure 11-28 come from less than six subjects, particularly for *NPb* with the whole hand condition (see Figure 11-28). This is possibly because NPb thresholds are higher (by more than 30 dB) than the P thresholds so that the masker could not mask the NPb channel within the range up to the 30 dB SL masker intensity.

In order to illustrate the responses of three receptor channels, as seen like the triplex model (see Figure 11-4), threshold contours were expressed in displacement then plotted for each subject and are shown in Figure 11-29 and Figure 11-30.

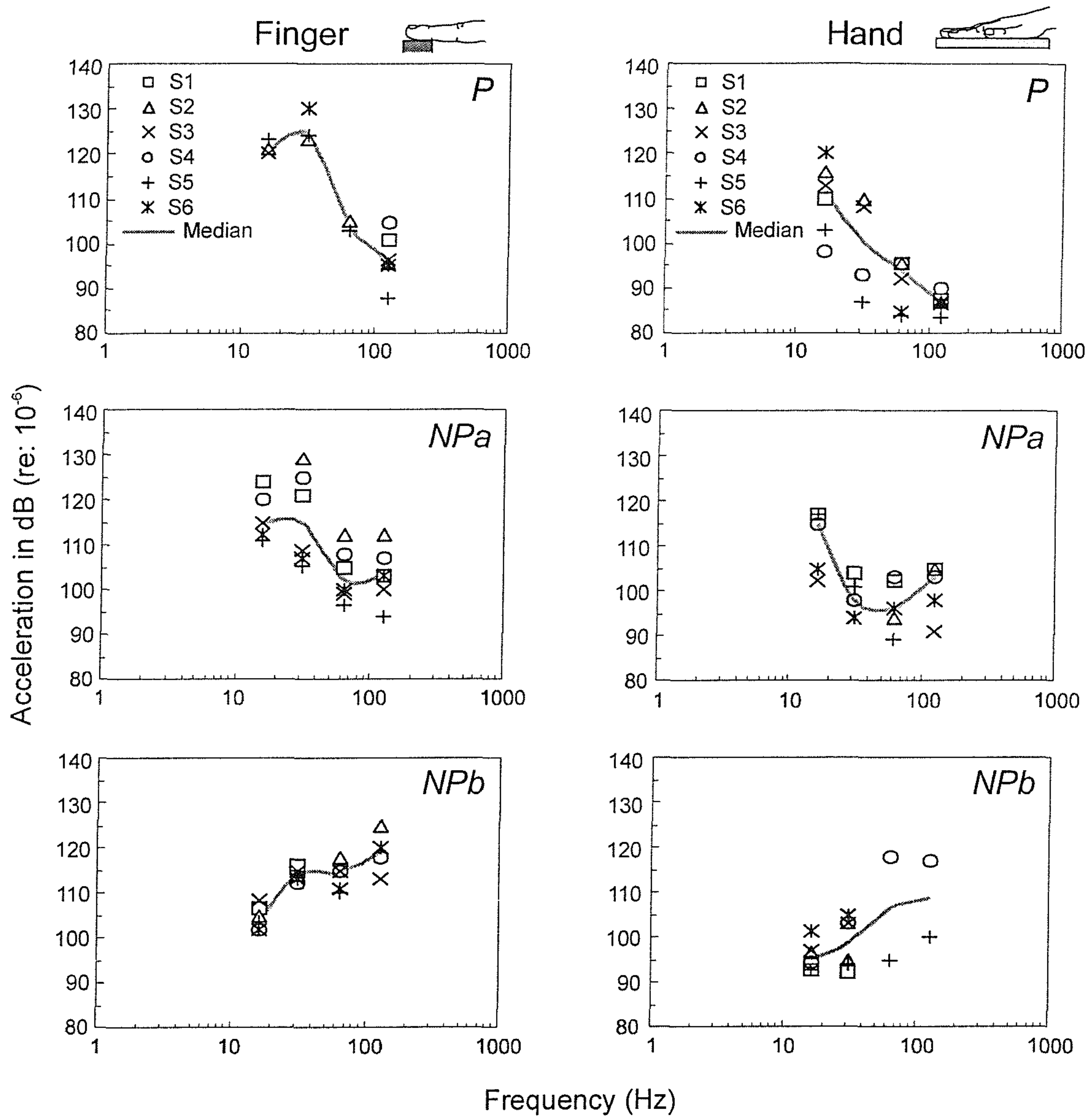


Figure 11-28 Threshold contours for three individual receptors (i.e. *P*, *NPa* and *NPb*) from six subjects determined with two different contact conditions (i.e. finger and whole hand). Data were taken from the markings of estimated detection responses from each measurement as presented through Figures 11-15 to 15-27. All data are expressed in acceleration (dB, re=10^{-6} ms^{-2} r.m.s.).

Although some of results contained incomplete contours, it is seen that most subjects showed lower *P* thresholds at high frequency and lower *NPb* thresholds at low frequency. This indicates that more than two receptor channels interacted for the determination of absolute thresholds, particularly with finger contact.

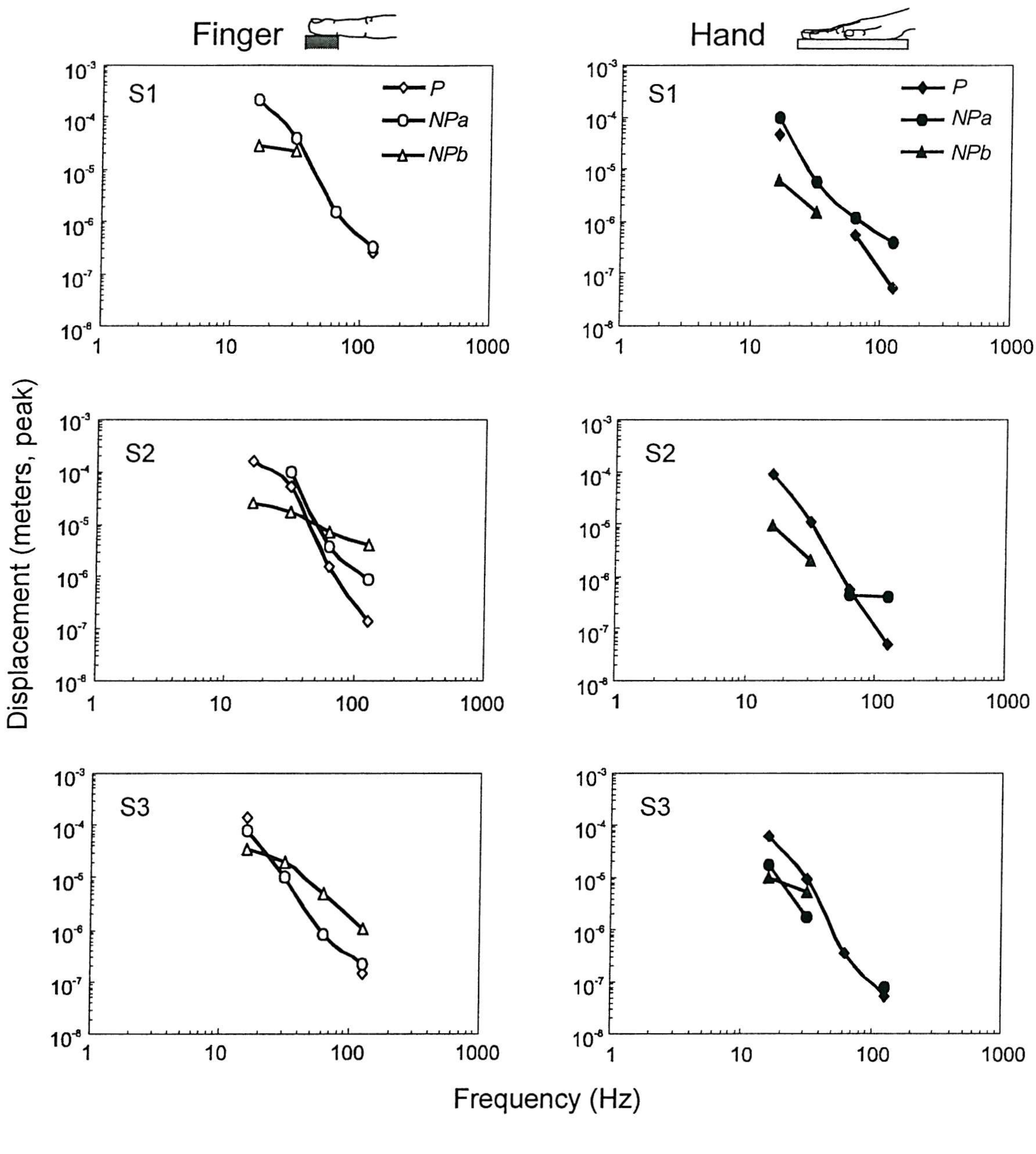


Figure 11-29 Responses of three independent receptors (i.e. *P*, *NPa* and *NPb*) for the detection of vibration at the fingertip and the whole hand. Individual subject data are shown and expressed in displacement (meters, peak).

As expected, hand contact produced lower *P* thresholds than finger contact, which may be due to spatial summation within the Pacinian channel. As a result, the *P* threshold contours of the hand were lower than the other threshold contours, so the absolute thresholds for other receptors were observed less often than with finger contact.

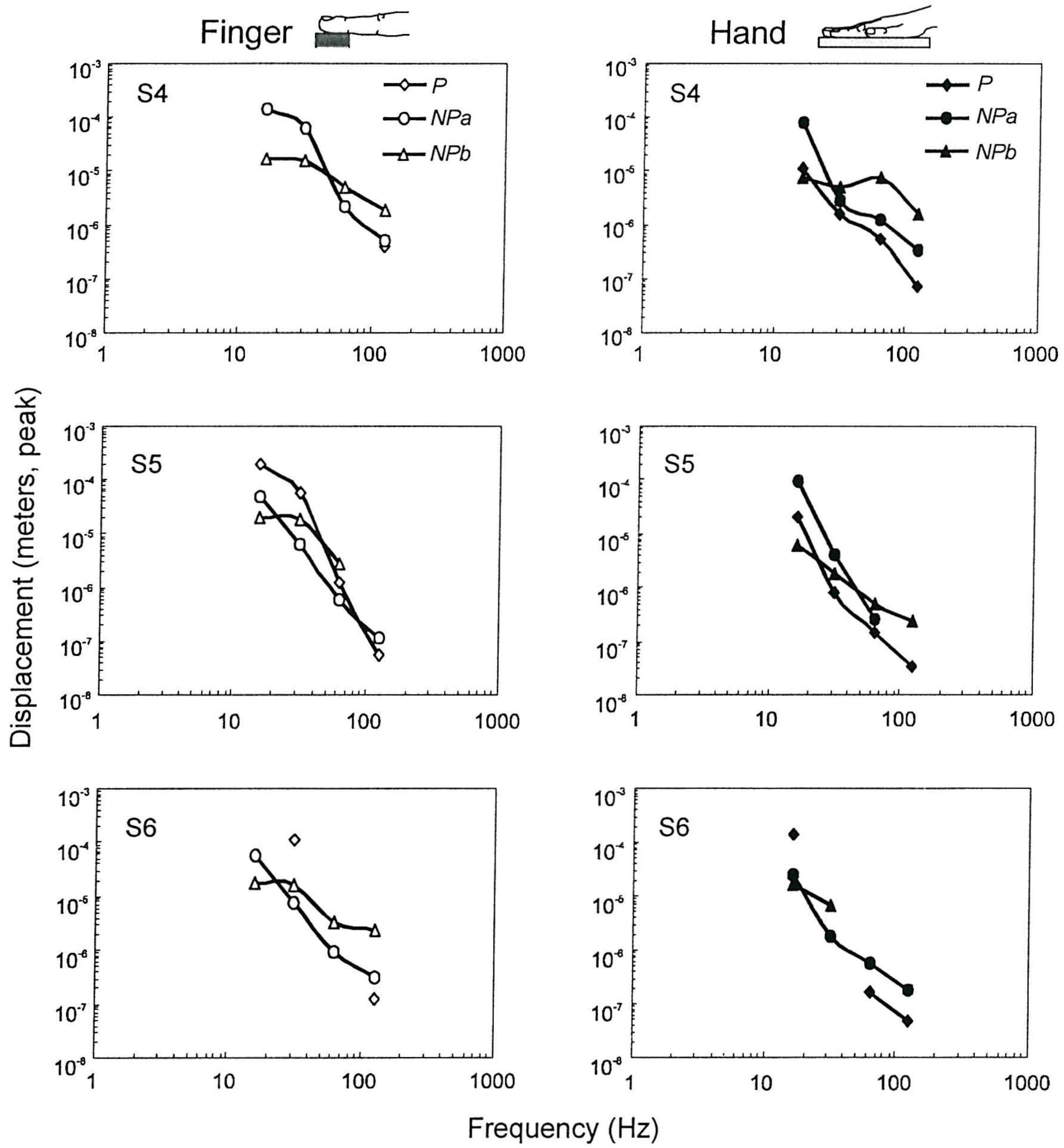


Figure 11-30 Responses of three independent receptors (i.e. *P*, *NPa* and *NPb*) for the detection of vibration at the fingertip and the whole hand. Individual subject data are shown and expressed in displacement (meters, peak).

Summarised threshold results from six subjects were determined taking account of the missing data and not merely taking a median value from the existing data. As stated before, the missing threshold values were assumed to be due to high threshold value, possibly above 30 dB SL, so that the masker was not sufficient to excite the receptor channel. The missing values therefore are expected to locate higher than any existing data. The procedure for summarising data with missing value was as follows:

1. Take the median value if six data values were available.
2. Take the average of the second and third highest measured value if five measured values were available.
3. Take the average of the highest and second highest measured value if four measured values were available.
4. Take the highest measured value if less than four measured values were available.

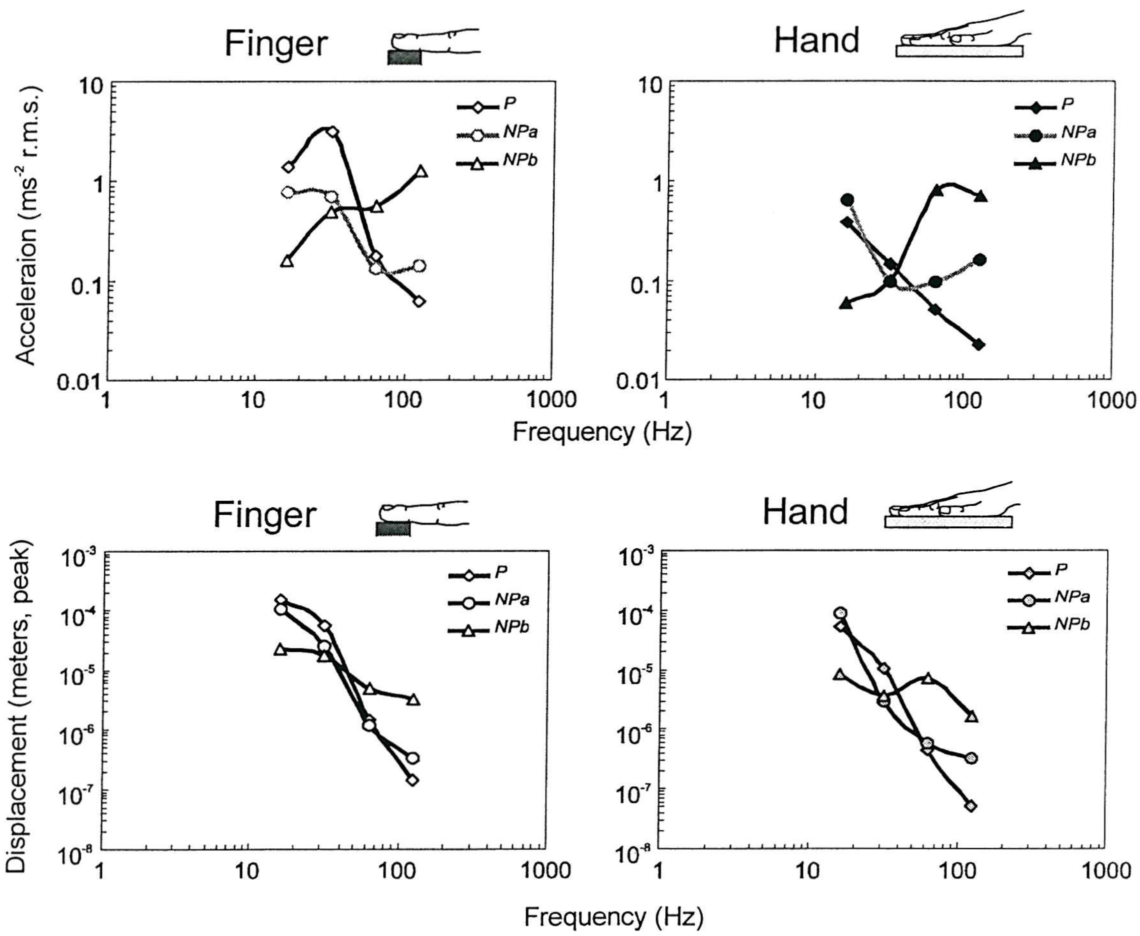


Figure 11-31 Median thresholds of *P*, *NPa* and *NPb* for the finger and the whole hand, expressed in acceleration and displacement. Median thresholds were estimated from missing data (see text, Section 11.8.2).

The summarised receptor thresholds obtained using the above procedure are shown in Figure 11-31.

Both the hand and the finger show that at least two receptor channels (*P* and *NPb*) are responsible for absolute thresholds with the most sensitive channel changing at intermediate frequencies. The displacement scale gave a clearer illustration of the thresholds of the different receptor channels, showing more simple threshold curves. The *P* and *NPa* thresholds displayed rather similar curves being close to each other in sensitivity, whereas the *NPa* thresholds displayed nearly a horizontal line, crossing over the *P* and the *NPa* threshold curves.

11.8.3 Identification of receptor channels

The last, but most exciting, step was to identify each channel according to the tactile receptor units. The threshold contours of each receptor obtained for the fingertip and the whole hand were compared (see Figure 11-32). It was not possible to apply statistical tests due to the missing values, so the identification process was performed visually.

The outcomes seem promising in that the threshold contours for all three receptor channels were almost identical in shape at the finger and at the hand.

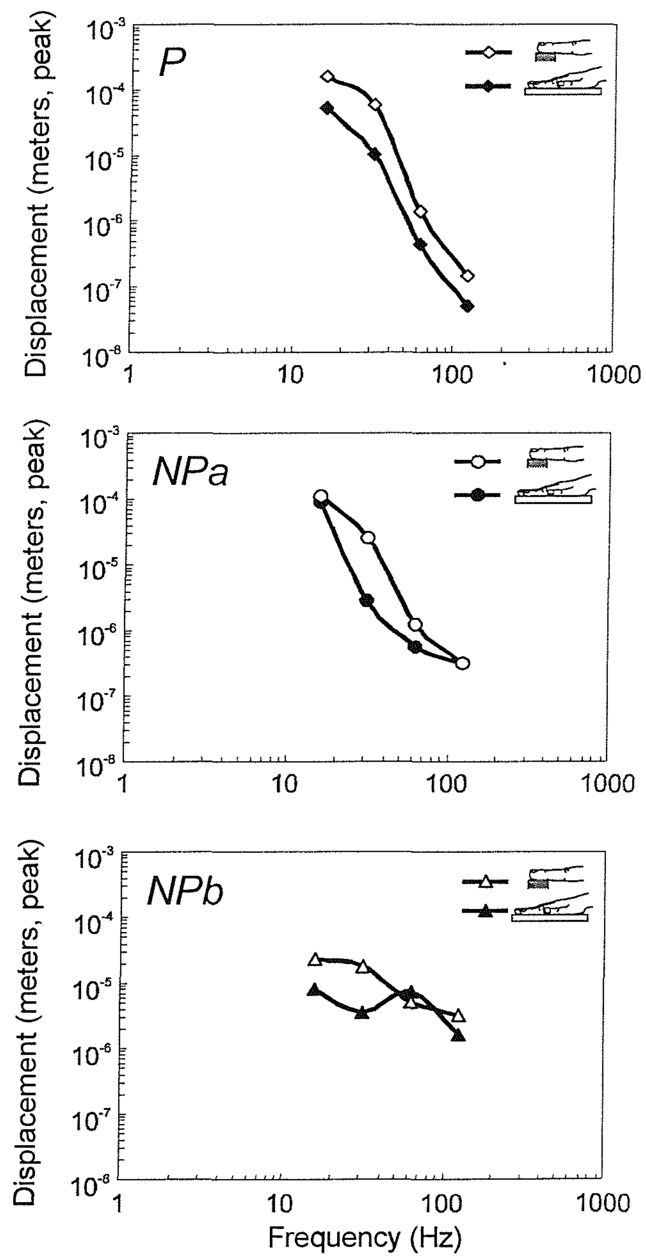


Figure 11-32 Comparison of absolute thresholds of individual receptor channels for finger contact and whole hand contact.

For the *P* channel, higher thresholds were obtained with finger contact and lower thresholds were obtained with hand contact.

This is consistent with spatial summation, so that this channel is almost certainly mediated by Pacinian corpuscles.

For the *NPa* channel, thresholds contours are very similar at the hand and the finger. That implies no spatial summation within the channel. The response shape has a little similarity to NPII model introduced from the triplex model by Gescheider *et al.* (1985) (see Figure 11-4). The response of NP II (SA II) receptors presented in a later study (Bolanowski *et al.*, 1988) was also a similar shape to the response of *NPa* thresholds shown in Figure 11-32. It is therefore suggested that the *NPa* channel is possibly mediated by SA II, Ruffini endings (see Section 2.2.2.1 for identification of SA II). The SA II receptors innervate with low density having some clustering around nails and finger joints (Johansson & Vallbo, 1979b; Ochoa and Torebjörk, 1983). They are characterised as a large receptive field and obscure boundaries and sensitive to remote stimuli particularly sensitive to directional skin stretch (Johansson *et al.* 1982a), which allows static receptor responses at high mechanical thresholds (Johansson, 1978), like a Pacinian receptors. Some neurophysiological studies reported that SA II units evoke no sensation when stimulated in isolation (Ochoa and Torebjörk, 1983; Wu et al., 1999). It was suggested that SA II units might contribute proprioreceptive feed-back to the motor control of the hand (Knibestöl and Vallbo, 1980), the conscious sensation may come through spatial summation (Ochoa and Torebjörk, 1983). However, there seems no psychophysical evidence whether SA II displays spatial summation (Bolanowski *et al.* 1988). The SA II responses have only been obtained with small contactor by Verrillo and Bolanowski (1986) and Gescheider *et al.* (1985), and the thresholds were relatively high; it may be possible that the SA II are capable of spatial summation.

The horizontal line seen as *NPb* channel thresholds shown in Figure 11-32 is typical of the response of FA I receptors. This was similar to the triplex model by Gescheider *et al.* (1985), so it is suggested that the *NPb* channel is possibly mediated by Meissner corpuscles (see Section 2.2.2.1 for identification of FA I).

11.8.4 Conclusions

Masked thresholds determined with vibration of the fingertip and the whole hand enabled individual responses from Pacinian and non-Pacinian systems to be identified.

It seems that three receptor channels, *P, NPa* and *NPb,* which have been identified as Pacinian, Ruffini and Meissner receptors, combine to detect hand-transmitted vibration. The sensitivity of each receptor depends on contact conditions: greater sensitivity was generally found for vibration of the whole hand contact compared with vibration of the fingertip.

These findings, which seem to provide a satisfying explanation of the results obtained in earlier studies, which are discussed further in General Discussion (Chapter 12).

CHAPTER 12

GENERAL DISCUSSION

12.1 INTRODUCTION

A scientific research is full of curiosities as it encounters the unknown. It also seeks to uncover what is desired to be known. One study stimulates another study, which stimulates several other studies, and so on and on forever, perhaps, whether or not the researcher has answered the original question.

This research is not an exception; the first experiment identified a curious uncertainty to be explained, which led to another experiment to uncover the facts and so on and on.

This chapter is aimed to progress a discussion, bringing the findings of all the studies together in an attempt to meet the initial objectives identified at the beginning of the thesis (Chapter 1).

12.2 INTERPRETATIONS OF THE FINDINGS

As a result of this investigation of psychophysical responses to hand-transmitted vibration, a parameter having a large role in the detection sensitivity of hand-transmitted vibration has been identified: increases in contact area can greatly increase vibration sensation.

The effect of contact area was initially observed in Study 2, then examined in Study 3. The finding was consistent with the spatial summation theory introduced by Verrillo (1963) and extended the theory to the whole area of the hand. A study by Verrillo demonstrated decreases in thresholds in proportion to an increase in contactor area (from 0.005 cm^2 to 5.1 cm^2) at frequencies above 60 Hz, this effect has been called 'spatial summation' and has been suggested as being due to the integration of responses via the Pacinian receptors (see Verrillo, 1963; Verrillo, 1966a; Verrillo, 1966b). This spatial summation was found within a localised area (the thenar eminence) on the hand.

Although the results were partly consistent with Verrillo's results, there was concern about some possible inconsistencies:

1. The spatial summation effect found in the current research was observed at both low and high frequencies (from 16 to 125 Hz);
2. The spatial summation effect was not exactly proportional to an increase in the contactor area.

Verrillo's study found that thresholds decreased by approximately 3 dB per doubling of area at frequencies above 60 Hz.

An attempt was therefore made to explain and interpret the slightly inconsistent spatial summation for hand-transmitted vibration. Two different approaches were undertaken: a consideration of the physiological factors (mechanoreceptor characteristics) and a consideration of physical factors (vibration transmission characteristics). In addition to vibration perception by mechanoreceptor units being dependent on the vibration stimuli entering the glabrous skin of the hand, there is a possibility of other physical factors influencing the detection of vibration by the receptors. A few alternative explanations have been considered, as shown below, which to take off for further discussion.

Spatial summation for hand-transmitted vibration may be due to:

1. Dominant response by Pacinian system, not non-Pacinian system
2. Contribution by variation in sensitivity over the hand
3. Contribution by transmission of vibration to the hand
4. Involvement of other receptors in the detection

12.2.1 Dominant response by Pacinian system, or non-Pacinian system?

The dependence of the spatial summation effect on high stimulus frequency has been interpreted as an indication that more than one type of mechanoreceptive system is involved in vibratory sensation; one receptor system is assumed to be sensitive to low-frequency vibration and not capable of producing spatial summation, while another receptor system is assumed to be sensitive to high-frequency vibration and summates activity over the excited area. A strong suggestion has been made that the Pacinian sensory system is capable of spatial summation (Verrillo, 1966a, 1968). So, it seems, there should be no spatial summation during exposure to low frequency vibration, but is that really true?

The results from Study 3 (see Chapter 6) displayed a decrease in perception thresholds with increasing contact area, from the distal part of the fingertip to the whole area of the hand at frequencies from 16 to 125 Hz. As can be seen from Figure 12-1, the reduction in threshold was almost the same amount over the frequency range, although some slopes are not linear. Taking from the linear line for 63 Hz thresholds, the decrement was approximately 3 dB per doubling of contact area, which is consistent with the finding of Verrillo (1963).

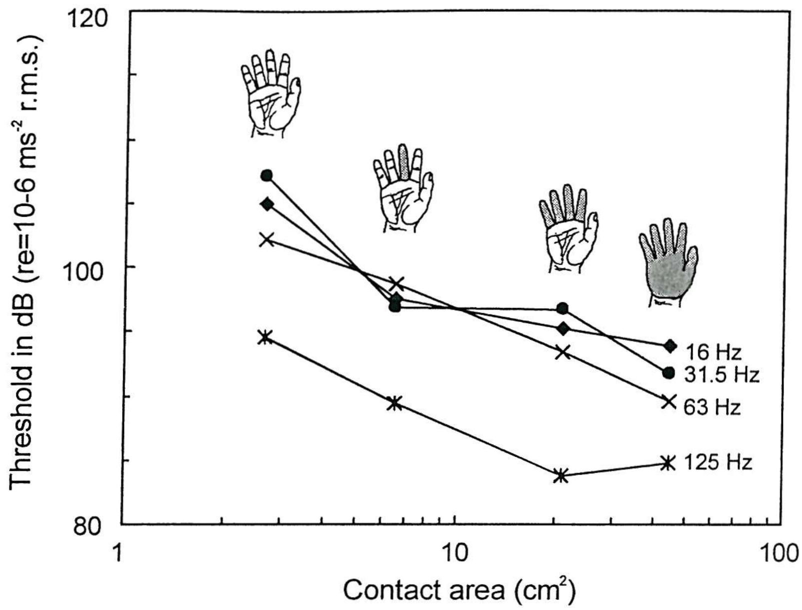


Figure 12-1 Threshold shifts as a function of contact area. Results from Study 3.

A possible explanation for the current findings would be that over the stimulus frequency range applied with all contact conditions in Study 3, vibration was primarily perceived via the Pacinian system and less mediated by the non-Pacinian system. Larger contact areas allow the U-shape of the Pacinian response curve wider and extend to the low frequency area otherwise dominated by the non-Pacinian system. This Pacinian-domination theory is also encouraged by the results of a study by Gescheider *et al.* (1978), which demonstrated spatial summation at low frequencies (from 25 to 700 Hz) when a rigid surround was not present around the contactor. In a few other experiments, it has been suggested that removal of the surround alters the sensitivities of the two systems in the low frequency range (below 25 Hz for the experimental conditions investigated by Gescheider *et al.*, 1978). The surround effect was also examined in part of Study 3; the results are shown in Figure 12-2 with thresholds expressed in displacement to allow a comparison with the results from Gescheider *et al.* (1978). The two results show a similar surround effect and a small difference in sensitivity that be explained by the different contact conditions: the U-shape curve of the Pacinian system was lower in Study 3 than that in the study of Gescheider *et al.* (1978), possibly due to the larger contact area in Study 3; the non-Pacinian responses in the study by Gescheider *et al.* (1978) provided a more distinctive horizontal line compared with that from Study 3, possibly due to a smaller gap in the Gescheider study.

There may be a trivial but interesting observation in Figure 12-2: the no-surround condition in Study 3 did not produce an exact U-shape curve of threshold contour at low frequency, the slope becomes more gentle as the frequency decreased, unlike the thresholds reported by Gesheider. One of the major differences between the present study and Gescheider's experiment was in the measurement location: Gescheider used the thenar eminence while Study 3 applied vibration to the distal middle finger. It is known that receptors are distributed with varying density over the glabrous skin of the hand (Johansson and Vallbo, 1979b), so the sensitivity of the receptor systems may differ at different areas of the hand. Considering the contact conditions used to investigate spatial summation, Verrillo examined within the thenar eminence, whereas Study 3 included the whole area of the hand. The conditions of Study 3 therefore differed in both contact location and the contact area.

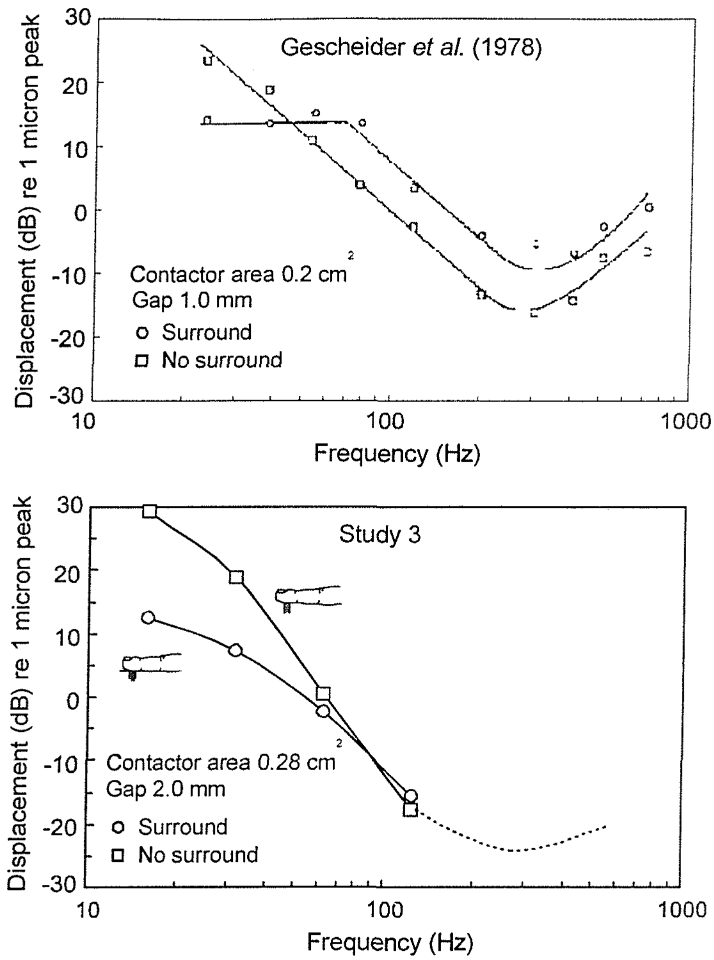


Figure 12-2 Effect of surround obtained by two different studies using similar contact area: upper graph by Gescheider *et al.* (1978), lower graph by Study 3 (see Chapter 6). Dotted line in lower graph is threshold with a surround estimated from the results of Study 2.

Although Pacinian dominance for all frequencies is still a possibility, this is not proven at low frequency with whole hand contact or, at least, not yet confirmed in this section.

12.2.2 Has a variation in sensitivity over the hand contributed to an apparent spatial summation?

An assumption has been made: if there were particular locations that are more sensitive to vibration stimuli than other locations, lower thresholds will be obtained when the sensitive area is in contact with the vibrating surfaces. This might also contribute to an apparent spatial summation as contact area increases from the finger to the whole area of the hand. Study 4 investigated whether sensitivity differs over the glabrous skin of the hand. Thresholds were determined using a surround to elicit responses via both Pacinian and non-Pacinian systems; there is apparently no previous study using a surround to elicit responses from the non-Pacinian system. The results showed no regional differences in the responses via the Pacinian system, but differences in responses via the non-Pacinian system. The non-Pacinian system was most sensitive at the distal fingers where the population of FA I (Meissner's corpuscle) is high (see Chapter 7). Considering the contact condition of STUDY 3, spatial summation was not contributed by a variation in sensitivity via non-Pacinian over the hand, because contact area was increased from the fingertip up to the whole hand: the fingertip was always in contact with the vibrating surface for all conditions.

As addressed in the last section (12.2.1), the effect of surround may be different at the fingertip than at the thenar eminence. It was found in Study 7 that non-Pacinian system was higher at the distal finger than at the thenar eminence. It may be possible that the non-Pacinian might respond at low frequency thresholds at the fingertip, even without a surround. A change in the effective receptor system caused by the use of a surround was only demonstrated by Gescheider *et al.* (1978) using the thenar eminence, so it remains uncertain whether the low frequency stimuli are mediated by the non-Pacinian or the Pacinian system when vibration is applied at the distal finger without a surround. If the non-Pacinian system was responsible for the perception of low frequency stimuli applied at the fingertip (with no surround) and to the whole hand, the spatial summation effect at low frequency might be explained by either: (i) biodynamic factors contributing to a lowering thresholds, or (ii) other receptors being involved in lowering thresholds.

12.2.3 Can the frequency dependence of the transmission of vibration lower thresholds?

It seems there are two reasons for placing a rigid surround around a probe: (i) producing a gradient stimulus which is detected by the non-Pacinian system, (ii) confining the vibratory stimulus to the region of application of vibration (preventing travelling waves spreading over the surface of the skin). Removal of the surround will allow the spread of vibration necessary for spatial summation. Although Gescheider, *et al.* (1978) stated that the effect of resonant characteristics of the skin may virtually be ignored since the source impedance (the vibrator) is very high relative to the impedance of the skin, it is uncertain how sensitivity is influenced by the transmission of vibration around the finger, hand and arm when large contact areas are involved, such as the whole hand.

From a mechanical point of view, the human hand is an elastic system capable of damping and transferring energy from one area to another. It is reasonable to assume that sensation is most likely in areas where the skin is most vibrated because of high transmission of vibration. Vibration frequency alters the transmission of vibration to and through the hand. As reported by Reynolds and Angevine (1977), at frequencies below 100 Hz most of the vibration directed into the fingers was transmitted to the hand, whereas at frequencies above 100 Hz the vibration tended to be localised to areas of the hand and fingers directly in contact with the vibrating surfaces.

An approach has been made in two studies (Studies 5 and 6) to investigate: (i) how a change of contact area affected the area at which the maximum sensation was produced and (ii) how a change of contact area affected the degree of sensation. There seemed to be dependence of subjective judgement on contact area and vibration frequency. The results of Study 5 indicate that with low frequency vibration (e.g. 8 Hz) at the fingertip, sensation tended to be produced at the proximal part of the finger or at the distal palm; sensation was likely to be produced towards the wrist and arm when the whole hand was in contact with the vibrating surface. With high frequency vibration, particularly at 125 Hz, sensation tended to be localised to the area directly in contact with the vibrating surface (see results in Figures 8-2 to 8-5). It was been clear from Study 4 that the Pacinian system has no regional variation in sensitivity over the hand, while the non-Pacinian system is most sensitive at the distal finger. It is therefore logical to assume that sensations appeared at areas where the vibration was most transmitted. Study 6 provided the curious finding that larger contact areas produced greater sensations for all frequencies, which is almost the same manner as spatial summation observed in Study 3.

Then a question arises: Does the greater transmission of vibration to the hand result in greater sensitivity to the stimulus? One might speculate that larger areas excite more Pacinian receptors and this produces the higher sensitivity. But, is the number of excited receptors really related to their sensitivity? An elegant demonstration of summation was made by Békésy (1958), determining vibrotactile thresholds at 150 Hz on the surface of the forearm using a large vibrating flame to provide two-point stimulation that set the distance between two contactors at either 0.5, 4.0 or 10.0 cm. It was found the thresholds were somewhat lower with a 4.0 cm separation, which was explained by the author: "addition of a second stimulating point within a certain 'action'". Further challenge was made by Craig (1968), who examined spatial summation using two sites of stimulation: at the thigh and the fingertips. The results showed spatial summation between the two vibrators on the thigh similar to that at the fingers, but no spatial summation when using a low frequency (9Hz) or with two different frequencies which are assumed to excite the same receptor (i.e. 160Hz and 360 Hz). The lowered thresholds with two-sited stimulation found in the study was likely due to other factors, such as contact force (suggested by Craig and Sherrick, 1969), and unlikely to be due to activity in a single afferent fibre. Referring *funneling action* demonstrated by Békésy (1957), with simultaneous vibration excitation using five vibrators lined up with 2 cm separation distances on the forearm provided subjective sensations only at the middle of the vibrators, with increased 'loudness' compared with the 'loudness' caused by the vibration from a single vibrator. This funneling action appeared at particular distance: sensation did not summate (become separated) if the distance between the two stimuli was to great, and the action becomes larger when the stimulated area on the skin is large. It seems that neural summation occurs when there is greater vibration transmission to excite receptors connected to a single afferent fibre. We can now return to the finding of Study 6 that whole hand contact produced greater sensations than smaller contact areas, even when the same stimulus magnitude was used. It is a possibility that the spatial summation effect found in Study 4 can be interpreted as: *increases in contact area resulted in greater transmission of* vibration to particular areas of the hand, which resulted in greater neural summation, greater sensitivity and lower thresholds.

Contact force is known to be a factor of contributing spatial summation; increase of contact force on the contactor can lower thresholds without increasing contact area (Craig and Sherrick, 1969). However the contact force was held at constant while increasing contact area in Study 3 so that this force effect can be excluded in the discussion.

12.2.4 Were other receptors involved in the detection of vibration?

As discussed in earlier sections, some explanations of the real or apparent spatial summation are based on the assumption that the stimuli were all detected via the Pacinian system. According to the studies completed by Verrillo and co-authors (e.g., Gescheider *et al.*, 1978; Verrillo, 1966b, 1966d, 1968), it seems unlikely that the non-Pacinian system plays a role in spatial summation, which is referred as FA I (Meissner corpuscles). However, a few psychophysical studies have provided evidence for separate responses within the non-Pacinian system: Gescheider *et al.* (1985), presented a triplex theory, Bolanowski *et al.*, (1988) identified four different responses known from neurophysiological evidence (see Johansson and Vallbo, 1979a; Vallbo and Johanson, 1984). There appears to be no evidence whether any of the non-Pacinian receptors (possibly SA II) has properties of spatial summation. It therefore became necessary, in the present research, to identify individual receptors responsible for the detection of hand-transmitted vibration stimuli, particularly at low frequency.

The final experiment, Study 8, was conducted to determine masked thresholds so as to obtain responses from individual receptors, both Pacinian and non-Pacinian systems. The masked threshold results indicated more than three interactive responses (referred as *P*, *NPa* and *NPb*) within the range of magnitudes of the masker stimuli employed. Further analysis allowed the display of threshold contours for three-individual receptor channels. One of these channels has been identified as the Pacinian receptor, for which whole hand contact produced lower thresholds than with finger contact, consistent with spatial summation. The other two channels, which assumed to be non-Pacinian receptors, were suggested as SA II (Ruffini) for *NPa* and FA I (Meissner) for *NPb*, from a comparison with the triplex model given by Gescheider *et al.* (1985). As seen in Figure 12-3, neither receptor appeared to show strong evidence of spatial summation, although the *NPb* receptor system showed a decrease in threshold at low frequency with the whole hand

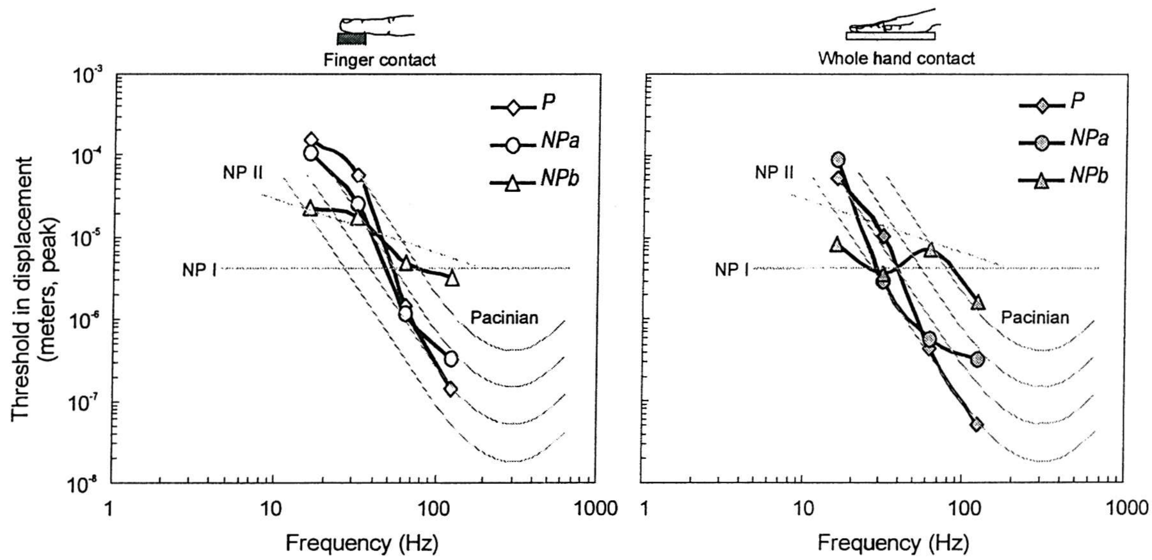


Figure 12-3 Results from Study 8: threshold response for each of three receptor channels obtained with the finger contact and the whole hand contact. The triplex-model by Gescheider *et al.* (1985) was overlaid for comparison.

contact compared with the finger contact. No further discussion was provided due to the inability to undertake a statistical examination of this matter.

While accepting the mediation by SA II receptors for hand-transmitted vibration, some doubts remain. The SA II receptors have been identified with their characteristics in several studies, which are found to be innervated in the same skin area as Pacinian (FA II) receptors, capable of thermal summation (Chambers *et al.*, 1972) and temporal summation (Bolanowski *et al.*, 1988; Gescheider *et al.*, 1985) but somehow do not respond to vibration stimuli (Wu *et al.*, 1999; Ochoa and Torebjörk, 1983), or the sensitivity was much low (Gescheider *et al.*, 1985; Johansson *et al.*, 1982a). These studies, especially in psychophsical study used a small contactor in order to excite SA II responses as well as minimise Pacinian responses: 0.01 cm^2 contactor used by Gescheider *et al.* (1985); 0.008 cm^2 contactor used by Verrillo and Bolanowski (1986). Since it is not known whether the NP II is capable of spatial summation (Bolanowski *et al.*, 1988), it is possible that the SA II became less sensitive due to the small contactor. It seems the discussion for this matter does not allow conveying further due to the lack of similar studies concerning whole hand contact condition.

All in all, it became a little clearer that absolute threshold for hand-transmitted vibration is determined by mediation of FA II at high frequency (over about 50 Hz) and FA I at low frequency (below about 40 Hz), with both condition in contact with the fingertip and with the whole hand. For supra-threshold, there is less firm suggestion which receptor is responsible for the detection since all three receptors become possible to be excited if the stimuli are above the threshold of the receptors. Apparent spatial summation was found in Study 5 showing an increase of magnitude sensation with increasing contact area, however it is not certain whether this was due to mediation of FA II or due to the effect of vibration transmission. Gescheider *et al.* (1997) found no dependence of difference threshold on skin temperature at 250 Hz, suggesting absence of Pacinian response in detecting difference threshold. The results of Study 7 on difference thresholds for whole hand contact condition showed no dependence of frequency, but unable to present which receptor was responding to the stimuli because the stimuli was used above threshold levels of all three receptors. It would be interesting to find out which receptor become responsible or how interact between three receptors when detecting supra-threshold stimuli.

12.3 SUMMARY

Having obtained those striking findings throughout a series of present studies, it is about time to 'uncover' some of uncertain findings and explanations from the previous studies, particularly the 'phenomena' on low frequency spatial summation observed in Study 3.

As agreed throughout the discussion that the spatial summation due to the whole hand contact was probably caused by mediation via Pacinian when exposed to high frequency stimuli (about above 50 Hz). However, for low frequency stimuli, one explanation provided in Section 12.3.1 (the response domination via Pacinian for all frequencies), is unlikely to be accepted according to the finding of Study 8: the non-Pacinian channel (possibly Meissner) was appeared to be responsible for low frequency (below about 50 Hz), and it *did* lower the threshold. This may be explained by biodynamic factor, as stated in 12.3.3, the change of contact area seems to cause altering vibration transmission and this can contribute summation of vibration energy to bring the sensitivity high.

Interactions of more than three receptor channels for threshold responses have been introduced from the results of Study 8 in both the finger and the hand contacts. Moreover, it was suggested that the three independent receptors, FA II, FA I and SA II, are possibly involved in detection when exposed to hand-transmitted vibration at supra threshold levels.

CHAPTER 13

CONCLUSIONS

13.1 INTRODUCTION

Sensitivity to hand-transmitted vibration has been quantified through the eight laboratory studies in the present research using three categories of psychophysical quantities: absolute thresholds, supra-thresholds (including difference thresholds, sensation magnitudes, sensation localisation) and masked thresholds.

In this final chapter, the initial objectives identified at the beginning of the thesis (Chapter 1) are revisited. The findings from each study are assembled to draw conclusions across the studies and, additionally, identify principal recommendations for further work in this research area.

13.2 FINDINGS FROM EACH STUDY

13.2.1 Absolute thresholds

➢ **Dependence on choice of psychophysical method**

The use of the 'forced-choice' procedure significantly lowered thresholds by 22% compared with the use of the 'yes-no' procedure ($p<0.05$). At 125 Hz, intermittent stimulation lowered thresholds compared with continuous stimulation ($p<0.01$). [Chapter 4]

➢ **No difference between two hand postures**

Two hand postures, with the whole hand pressing a flat plate or grasping a handle, made no difference to thresholds ($p>0.05$). [Chapter 5]

➢ **Changes in sensitivity caused by a surround**

Stimulus conditions can modify the detection sensitivity via Pacinian and non-Pacinian sensory systems. Placing of a 10 mm diameter surround around a 6 mm diameter probe at the fingertip lowered thresholds by about 16 dB at 16 Hz and elevated thresholds by about 6 dB at 125 Hz. [Chapter 6]

➢ **Increase in sensitivity caused by increase in contact area**

Increasing contact area (from the fingertip to the whole hand) lowered thresholds by about 10 dB at both low and high frequencies. There was a significant decrease in thresholds when changing contact from the fingertip to the whole finger. [Chapter 6]

➢ **Regional difference for Pacinian perception, but less so for non-Pacinian perception**

There are regional differences in sensitivity for the non-Pacinian system over the glabrous skin of the hand (most sensitive at the distal part of the finger). No regional differences in sensitivity were found for the Pacinian system. [Chapter 7]

13.2.2 Supra-thresholds

13.2.2.1 Localisation of sensation

➢ **The localisation of sensation is dependent on vibration frequency**

The localisation of the sensations produced by hand-transmitted vibration were greatly influenced by stimulus frequency; low frequencies brought sensations towards the wrist and arm, high frequencies left sensations close to the area where the skin was in contact with the vibrating surface. [Chapter 8]

➢**The localisation of sensation is dependent on contact area**

The effect observed above was greater when vibration was applied with a larger contact area. [Chapter 8]

➢ **A hand gripping posture gave greatest sensations at the proximal end of the fingers and in the knuckle area.**

Sensations were localised in different positions with the handle grasping posture and the hand pressed on a flat table. Even though vibration exposure was in the same area of the hand, a handle grasping posture produced sensations mostly around the proximal area of fingers and the distal area of palm, whereas the hand on a flat table produced sensations over the whole area of the hand. [Chapter 8]

13.2.2.2 Sensation magnitude

- **Greater in sensation at low frequency and less at high frequency**

Sensation magnitudes were higher at lower frequencies (i.e. 8 and 16 Hz), relative to the reference frequency at 31.5 Hz, whereas sensation magnitudes were lower at higher frequencies (i.e. 63 and 125 Hz) or there was no change in sensitivity, relative to the reference frequency at 31.5 Hz. [Chapter 9]

- **Increase in sensation greatness with increasing contact area**

Increases in contact area, from the fingertip to the whole hand, resulted in significantly greater sensation magnitudes ($p<0.05$) while stimulus magnitude was kept at constant. [Chapter 9]

13.2.2.3 Difference thresholds

- **Difference thresholds were nearly proportional to the stimulus intensity (consistent with Weber's law)**

Difference thresholds for hand-transmitted vibration were almost proportional to the stimulus magnitude, with magnitudes in the range 2 to 5 ms^{-2} r.m.s. [Chapter 10]

- **No frequency dependence in relative difference thresholds ($\Delta I/I$ = 0.15 to 0.18)**

The relative difference threshold (= difference threshold value divided by reference magnitude) was independent of frequency, unlike absolute thresholds ($p>0.1$). This was seen at two vibration magnitudes. [Chapter 10]

13.2.3 Masked thresholds

- **Masking only appeared when the masker and the test stimuli excited the same receptor**

The results seem consistent with the masking theory: masked thresholds are elevated with increasing magnitudes of the masker stimulus when the masker and the test stimuli are perceived via the same receptor channel (with a slope of 1.0), and masked thresholds are not elevated when the masker and the test stimuli are perceived via different receptors. [Chapter 11]

- **Three receptors may be involved in the detection of hand-transmitted vibration**

The masking functions obtained from the masked threshold results contained more than one non-Pacinian channel, indicating that at least three receptors interact in the detection of vibration stimuli. This was found with both contact conditions (finger contact and whole hand contact). [Chapter 11]

- **Whole hand contact increased Pacinian sensitivity**

Perception thresholds of each single receptor were estimated for two contact conditions: finger contact and whole hand contact. Threshold contours for Pacinian perception were lower with whole hand contact than with finger contact. Other receptors (in the non-Pacinian system, *NPa* and *NPb*, suggested as SA II and FA I, respectively) showed virtually no change in threshold contours between finger and hand contact. [Chapter 12]

13.3 CONCLUSIONS ACROSS THE STUDIES

A consistent finding from the studies was that contact of the whole area of the hand with a vibrating surface provided greater sensitivity in the detection of hand-transmitted vibration than contact with a smaller area of the hand. This was evident at frequencies between 8 and 500 Hz in studies determining absolute thresholds (Chapter 6) and sensation magnitudes (Chapter 9). Contact area appeared to be a principal factor influencing sensitivity to hand-transmitted vibration: decreasing absolute thresholds and increasing sensation magnitudes with increasing contact area up to the whole area of the hand. This was no difference in sensitivity between two different hand postures (palm pressing on a flat table and grasping a handle) for either absolute thresholds (Chapter 5) or sensation magnitudes (Chapter 9).

When hands are exposed to high magnitude of vibration stimuli, low frequency stimuli produce greater sensations than high frequency stimuli of the same acceleration (Chapter 9). However, the ability to discriminate stimulus magnitudes (difference thresholds) was about 15 to 18 % of the magnitude and independent of frequency.

It might be assumed that the characteristics of vibration that give the greatest sensations also produce the greatest risks of injury to the human hand. This would imply that the low frequencies that are predominant on many tools are likely to produce more discomfort to users than the high frequencies. A reduction of the vibration magnitude on a tool should be no less than about 18% in magnitude, if users are to recognise that the tool has been improved. A different application might be found in the provision of tactile information for disabled persons: perceptible vibration stimuli are required without being too intense or too weak. It may be possible to produce vibration at a variety of magnitudes so as to give some information (e.g. alarms, warnings, distance to obstacles); these stimuli should be much more than 18% different in magnitude so that the users can recognise the different meaning of different stimuli.

The experimental results have mostly been explained by the response characteristics of mechanoreceptors, so as to advance understanding of the sensory mechanisms involved in the perception of hand-transmitted vibration. Identification of receptors was achieved by the determination of masked thresholds in the last study (Chapter 11). It seems that hand-transmitted vibration stimuli are mediated by at least three independent receptors: FA II (Pacinian corpuscles), FA I (Meissner's corpuscles) and, possibly, SA II (Ruffini endings). The response characteristics of these receptors are likely to be reflected in the various psychophysical responses.

For absolute thresholds, the FA II receptors were found to be dominantly responding at high frequencies (about above 50 Hz) and capable of spatial summation, seen as a lowering of thresholds with increasing contact area from the fingertip up to the whole area of the hand (Chapter 6). The FA I receptors are responsible for the perception of low frequency stimuli (below about 40 Hz), and do not seem to display spatial summation, but show decreased thresholds when a surround is placed around a vibrating probe. The FA I response appeared to exist with low frequency stimuli applied to the fingertip and the whole hand, even without a surround. The SA II response, displayed similar frequency dependence to FA II thresholds, with slightly less sensitivity than the FA II receptors. Although the FA II were observed to show no spatial summation, the possibility of spatial summation is implied in some of the literature.

A reduction in thresholds at low frequency with increasing contact area cannot be explained by the mechanoreceptor characteristics. However, a follow-up study of the localisation of sensation (Chapter 8) suggested the possibility that a biodynamic effect lowers thresholds by the transmission (and amplification) of vibration to other areas of the hand.

For difference thresholds, there was no frequency dependence over the frequency range 8 to 500 Hz by whole hand. This might suggest that the response is mediated by a single receptor system, either Pacinian or non-Pacinian receptor system (Chapter 10). Although no evidence is available from the present results, it seems more likely that the non-

Pacinian receptors were responsible for mediation at the supra-threshold levels, according to evidence in the relevant literature.

13.4 RECOMMENDATIONS FOR FURTHER WORK

For sure, there must be no end of research in this area if we are to make our future brighter. Here are a few areas of possible future work that attracted the author and might provide further understanding of mechanisms responsible for the perception of hand-transmitted vibration, particularly in relation to whole hand contact with the source of vibration.

Is the surround effect at the fingertip similar at other areas of the hand?

As seen in the present research, the fingertip area is the most sensitive area for response via the FA I receptors (Chapter 7). Because much research has investigated the thenar eminence to establish mechanisms for vibrotactile sensitivity, it would be sensible to identify whether the mechanisms are the same for all glabrous areas of the hand.

Does spatial summation occur via Pacinian receptors when determining psychophysical responses to hand-transmitted vibration other than absolute thresholds?

A spatial summation effect was found in the present research: a decrease in absolute thresholds with increasing contact area (Chapter 6) and an increase in sensation magnitudes with increasing contact area (Chapter 9). Further interests may be directed to spatial summation at supra-threshold levels (e.g. difference thresholds, equal sensation contours); the results would add to knowledge of the detection ability of human hands and also provide evidence of whether Pacinian or non-Pacinian receptors are responsible for the detection of hand-transmitted vibration.

Do SA II (Ruffini) receptors display spatial summation?

As stated in Section 13.2, there seems to be no firm evidence of spatial summation via SA II receptors. More work in this area would help to identify the interactions between receptors responsible for vibration perception.

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APPENDIX A

HEALTH QUESTIONNAIRE FOR SUBJECTS

HEALTH QUESTIONNAIRE FOR SUBJECTS

Ref. No. ___________

Name: ________________________ Age: ____________

Nationality: ________________________ Height: ______ cm Weight: __________ kg

Dominant hand: Right ☐ Left ☐ Occupation: Student ☐ Staff ☐ Other ☐

Please answer the questions below. All information will be treated as CONFIDENTIAL.

1 Do you smoke?

YES NO If yes→Specify the number, [ ] of cigarettes / day

2 How much alcohol do you consume weekly?

Never *1-3 units* *4-6 units* *More than 6 units*

3 Do you take any drugs or medication?

YES NO If yes, please specify ________________________

4 Have you had any hand or wrist surgery?

YES NO If yes, please specify ________________________

5 Have you had any burn or scars on your hands or fingers?

YES NO If yes, please specify ________________________

6 Do you suffer from any disease such as:

Diabetes *Vascular problems* *Neuropathy problems* *Others* ________________________

None

7 Have you been exposed to severe or long periods of vibration at the hand?

YES Vibration tools Motor bike Others ________________________

NO

Thank you very much.

APPENDIX B

INSTRUCTIONS FOR SUBJECTS

B1 INSTRUCTIONS FOR SUBJECTS (STUDY 1)

Thank you for agreeing to participate as a subject in this research project.

The aim of this experiment is to measure vibration perception thresholds (just perceptible level of vibration) at the fingertip with three different measurement methods (Method A, Method B and Method C).

Please read carefully and follow the instructions indicated by the experimenter.

---

1 Before the experiment:

- Your skin temperature will be measured. The test will be allowed to proceed if the temperature is higher than 29 Celsius.

2 To begin the experiment:

- Sit comfortably and rest your right arm on the vibrometer.
- Place your right middle finger over the probe.
- Maintain a downward push force at 2N while looking at the force meter.
- Wear the ear defenders in order to prevent you from hearing the vibrations.

3 During the experiment:

<Method A>

- Hold the response button in your left hand.
- Magnitude of vibration stimuli will be increased and decreased continuously according to your responses.
- Your task is to: PRESS the response button while you feel a vibration, RELEASE the button when the vibration is no longer be felt.
- A test will be terminated in 30 seconds.

<Method B>

- A series of single vibration stimulus (lasting one second each in duration) will be presented.
- The light tells you when the stimulus is generated.
- Your task is to judge whether you felt the vibration stimuli or not.

  Say "YES" or "NO", each time.

Cont.

<Method C>

- A series of two stimuli (lasting one second each in duration) will be presented; one of the stimuli contains very faint vibration
- The light tells you when the stimuli are generated.
- Your task is to judge whether the first or the second stimulus contained the vibration.
  Say "FIRST" or "SECOND", each time

NOTE:

- The test will be repeated four times (with four different vibration frequencies) for each method.

Thank you very much for your co-operation.

B2 INSTRUCTIONS FOR SUBJECTS (STUDY 2)

Thank you for agreeing to participate for this research project.

The aim of this experiment is measure vibration perception thresholds (just perceptible level of vibration) at the fingertip and the whole hand with two hand postures. The experiments consist of three sessions.

Please read carefully and follow the instructions below.

---

1 Before the experiment:

- Your skin temperature will be measured. The test will be allowed to proceed if the temperature is higher than 29 Celsius.
- Dimensions of your dominant hand will be measured.

2 To begin the experiment:

- Sit comfortably with your arm supported by the armrest provided.
- Place your hand/finger on to the measurement source provided by the experimenter.
- Maintain a downward contact force indicated by the experimenter while looking at the force meter.
- Wear the ear defenders in order to prevent you from hearing the vibrations.

3 During the experiment:

- A series of two stimuli (lasting 3 seconds in duration) will be generated; one of the stimuli contains vibration. The light tells you when the stimuli are generated.
- Your task is to judge whether the first or the second stimuli contained the vibration.

  Say "FIRST" or "SECOND", each time.

NOTE:

The test will be repeated seven times (with seven different frequencies) in each session.

Thank you very much for your co-operation.

B3 INSTRUCTIONS FOR SUBJECTS (STUDY 3)

Thank you for agreeing to participate as a subject for this research project.

The aim of this experiment is to measure vibration perception thresholds (just perceptible level of vibration) with various contact conditions.

Please read carefully and follow the instructions below.

1 Before the experiment:

- Your skin temperature will be measured. The test will be allowed to proceed if the temperature is higher than 29 Celsius.

2 To begin the experiment:

- Sit comfortably with your arm supported by the armrest.
- Place your dominant finger/hand according to the test condition being measured.
- Maintain a downward contact force indicated by the experimenter while looking at the force meter.
- Wear the ear defenders in order to prevent you from hearing the vibrations.

3 During the experiment:

- A series of two stimuli (lasting 3 seconds each in duration) will be generated; one of the stimuli contains vibration. The light tells you when the stimuli are generated.
- Your task is to judge whether the first or the second stimuli contained the vibration.

  Say "FIRST" or "SECOND", each time.
- Please maintain your hand posture at a constant force.

NOTE:

- The test will be repeated four times (with four different frequencies) in each contact condition.
- The dimensions of your dominant hand will be measured.

Thank you very much for your co-operation.

B4 INSTRUCTIONS FOR SUBJECTS (STUDY 4)

Thank you for agreeing to participate as a subject for this research project.

The aim of this experiment is to determine vibration perception thresholds (just perceptible level of vibration) at several locations over the hand.

Please read carefully and follow the instructions below.

---

1 Before the experiment:

- Your skin temperature will be measured. The test will be allowed to proceed if the temperature is higher than 29 Celsius.

2 To begin the experiment:

- Sit comfortably and rest your right arm on the vibrometer.
- Place the measuring location in the hand (indicated by the experimenter) over the probe of the vibrometer.
- While looking at the force meter, press down gently on the probe until the needle on the force feedback unit reaches the "ON" position. Please maintain the pressure throughout the test.
- Wear the ear defenders in order to prevent you from hearing the vibrations.
- Hold the response button in your left hand.

3 During the experiment:

- Magnitude of vibration stimuli will be increased and decreased continuously according to your responses.
- Your task is to: PRESS the response button while you feel a vibration, RELEASE the button when the vibration is no longer be felt.
- A test will be terminated in 30 seconds.
- Repeat the cycle until the experimenter informs you the test is complete.

Thanks for your co-operation

B5 INSTRUCTIONS FOR SUBJECTS (STUDY 5)

Thank you for agreeing to participate as a subject in this research project.

The aim of this experiment is to determine the relationship between the sensations of vibration with contact area, frequency and magnitude.

Please read carefully and follow the instructions below.

---

1 Before the experiment:

- Your skin temperature will be measured. The test will be allowed to proceed if the temperature is higher than 29 Celsius.

2 To begin the experiment:

- Sit comfortably with your arm supported by the armrest.
- Place your right finger/hand (indicated by the experimenter) on the provided contact source.
- Maintain a downward contact force (indicated by the experimenter) while looking at the force meter.
- Wear the ear defenders in order to prevent you from hearing the vibration.

3 During the experiment:

- A series of single stimulus (lasting 5.0 seconds in duration) will be presented.
- Your task is to judge which part of the hand (or arm) you felt the sensation the most.
- Reply, after referring to the given diagram, with the corresponding combination of letter and number (e.g. A1)

Thank you very much

B6 INSTRUCTIONS FOR SUBJECTS (STUDY 6)

Thank you for agreeing to participate as a subject in this research project.

The aim of this experiment is to determine the relationship between the sensations of vibration with contact area, frequency and magnitude.

Please read carefully and follow the instructions below.

---

1 Before the experiment:

- Your skin temperature will be measured. The test will be allowed to proceed if the temperature is higher than 29 Celsius.

2 To begin the experiment:

- Sit comfortably with your arm supported by the armrest.
- Place your right finger/hand (indicated by the experimenter) on the provided contact source.
- Maintain a downward contact force (indicated by the experimenter) while looking at the force meter.
- Wear the ear defenders in order to prevent you from hearing the vibration.

3 During the experiment:

<Frequency comparison test>

- A series of two stimuli (lasting 2 second each in duration) will be presented. The first one is a reference stimulus and the second one is a test stimulus.
- You are told that the reference stimulus represents "100". Your task is to reply with a number that represents how great the magnitude of sensation of the second stimulus is, relative to the reference (e.g. 150).

<Contact comparison test>

- A series of two stimuli (lasting 2 seconds each in duration) will be presented. The first one is a reference stimulus and the second one is a test stimulus.
- Place your whole finger when receiving the reference stimulus, then change the contact condition as indicated by the experimenter when receiving the test stimulus.
- You are told that the reference stimulus represents "100". Your task is to reply with a number that represents how great the magnitude of sensation of the second stimulus is, relative to the reference (e.g. 150).

B7 INSTRUCTIONS FOR SUBJECTS (STUDY 7)

Thank you for agreeing to participate as a subject for this research project.

The aim of this experiment is to determine difference thresholds (minimum change of stimulus magnitude noticed by subjects) with a handle-grasping posture.

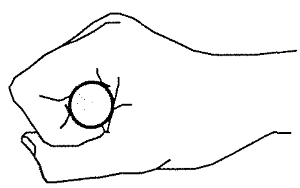
Please read carefully and follow the instructions below.

1 Before the experiment:

- Your skin temperature will be measured. The test will be allowed to proceed if the temperature is higher than 29 Celsius.
- Dimensions of your dominant hand will be measured.

2 To begin the experiment:

- Sit comfortably with your arm supported by the armrest.
- Grip the handle lightly with your dominant hand as like the figure beside.
- Maintain a downward push force at 10 N while looking at the force meter.
- Wear the headphones in order to prevent you from hearing the vibrations.



Handle grasping posture

3 During the experiment:

- You will feel a set of two vibration stimuli (lasting 3 seconds in duration).
- The light tells you when the stimuli are generated.
- Your task is to judge whether the first or the second stimuli was greater.
  Say "FIRST" or "SECOND", each time.
- Please maintain the hand posture at the constant push force.

NOTE:

Six tests will be performed with different frequencies in a session.

Thank you very much for your co-operation.

B8 INSTRUCTIONS FOR SUBJECTS (STUDY 8)

Thank you for agreeing to participate as a subject for this research project.

The aim of this experiment is to determine vibration perception thresholds (just perceptible vibration level) with various background vibration.

Please read carefully and follow the instructions below.

1 Before the experiment

- Your skin temperature will be measured. The test will be allowed to proceed if the temperature is higher than 29 Celsius.

2 To begin the experiment:

- Sit comfortably with your arm supported by the arm rest. Place your dominant finger/hand on the flat table.
- Maintain a downward push force while looking at the force meter.
- Wear the ear defenders in order to prevent you from hearing the vibrations.

3 During the experiment:

Measurements will be performed with two procedures: firstly "Unmasked Test" (without background vibration), secondly "Masked Test" (with background vibration).

<Unmasked Test>

1. Two stimuli will be presented, one stimulus contains vary faint vibration (lasting 0.6 second each in duration).
2. Your task is to judge whether the first or the second stimulus contained vibration.
3. Say "FIRST" or "SECOND", each time.

<Masked Test>

1. One single stimulus (= test stimulus) will be presented followed by two stimuli (=observation stimuli) covered with background vibration: one of the observation stimuli contains vibration as the same stimulus as the test stimulus.
2. Your task is to judge whether the first or the second stimulus contained the test stimulus. Say "FIRST" or "SECOND", each time.

--- Note ---

- A light tells you when the stimuli are generated.
- The measurement will be repeated several times with various intensities of background vibration.

Thank you very much for your co-operation.

APPENDIX C

PROGRAMMES USED FOR LABORATORY STUDIES

```
\                           13:40 05.02.01
\
\ SCREEN TO M3 FILES (YES-NO METHOD)
\ FOR STUDY 1
\
\               CREATED BY MIYUKI M
\
\
\ CREATE FILES                 12:58 15.01.99
  99 120 NDEL 0.0 := 13 PARA  1.0 := 11 PARA
: TAPER    " TAPER" BRUN COPY  END-MODULE ;

\ CREATE PAUSE
  140 DEL

\ CREATE 8 Hz
\ 8.0 := 14 PARA 400.0 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 50 50 TAPER

\ CREATE 16 Hz
\ 16.0 := 14 PARA 400.0 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 50 50 TAPER

\ CREATE 31.5 Hz               11:39 15.01.99
  31.5 := 14 PARA 700.28 := 10 PARA 0.05 := 12 PARA 99 SINE
  1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
  99 100 85 85 TAPER

\ CREATE 63.0 Hz
\ 63.0 := 14 PARA 1400.56 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 150 150 TAPER
\ CREATE 125.0 Hz
\ 125.0 := 14 PARA 2500.0 := 10 PARA 0.03 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 300 300 TAPER

\ CREATE 250.0 Hz                 11:13 15.01.99
\ 250.0 := 14 PARA 5000.0 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 500 500 TAPER

\ CREATE 500.0 Hz
\ 500.0 := 14 PARA 8064.51 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 1000 1000 TAPER

\ TAPER                        18:15 04.01.99
  99 DEL

\ CREATE LIGHT
  200 201 NDEL
  2.5 := 12 PARA 1.0 := 11 PARA
  -2.5 := 13 PARA  200 SINE

\ CREATE OFF LIGHT
  0.0 := 12 PARA 1.0 := 11 PARA
  -2.5 := 13 PARA 201 SINE

\ CREATE OTHER FILES              16:25 08.12.97
   1.2589 := constant 100 101 FILE*
   1.5849 := constant 100 102 FILE*
   1.9953 := constant 100 103 FILE*
   2.5119 := constant 100 104 FILE*
   3.1623 := constant 100 105 FILE*
   3.9811 := constant 100 106 FILE*
   5.0119 := constant 100 107 FILE*
   6.3096 := constant 100 108 FILE*
   7.9433 := constant 100 109 FILE*
  10.0000 := constant 100 110 FILE*
  12.5893 := constant 100 111 FILE*
  15.8489 := constant 100 112 FILE*

\                                 16:25 08.12.97
  19.9526 := constant 100 113 FILE*
  25.1189 := constant 100 114 FILE*
  31.6228 := constant 100 115 FILE*
  39.8107 := constant 100 116 FILE*
  50.1187 := constant 100 117 FILE*
  63.0957 := constant 100 118 FILE*
   0.0000 := constant 100 120 FILE*
```

Figure C1-1 Study 1: Absolute thresholds, Method B (Up-down, yes-no), set up stimulus.

```
\                              13:40 05.02.01
\
\ M4  BATCH JOBS (YES-NO METHOD)
\ FOR STUDY 1
\
\                CREATED BY MIYUKI M
\
\ JOB TO PRESENT STIMULI                11:00 15.01.99
\ NEED FILES : 100  = REFERENCE
\ 101 = REF+1, 102 = REF+2, 103 = REF+3, 104 = REF+4, 105 REF+5
\ 106 = REF+6, 107 = REF+7, 108 = REF+8, 109 = REF+9, 110 REF+10
\ 111 = REF+11, 112 = REF+12, 113 = REF+13, 114 = REF+14,
\ 115 = REF+15, 116 = REF+16, 117 = REF+17, 118 = REF+18
\ 140 = PAUSE, 200 = LIGHT, 201 = OFF LIGHT

: MODULE ;
: LXTRACT  " LXTRACT"  BRUN COPY  END-MODULE ;
  INTEGER resp INTEGER countn INTEGER dim 1 := dim
  INTEGER current INTEGER ifl INTEGER repeats INTEGER county
  INTEGER correct   INTEGER ok
  REAL rms   REAL value
  VARIABLE VOCVAR VARIABLE DPVAR
        value 1.0 := value

\ ORDER 1                       12:59 15.01.99
: ORDER1
  ifl current + 140 2 17 MERGE   \ STIMULUS
  200 201 2 18 MERGE   \ LIGHT
  1 DEL 32767 DEL
 ." DATA DATA " CR           \ RUN DATA

  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  2.0 := 5 PARA
  DATA
 ."              WEBER'S LAW PROGRAM " CR
 ."              ***** Order 1 ***** " CR
  0.1 0.9 1 32767 LXTRACT
  32767 STATS 5 CB := rms
```

```
\                              11:05 15.01.99
." TEST FILE : " ifl current + . CR CR
." Did you feel the stimulus ? "
  CR 1000 8 BEEP
." Enter 0 or 1 " #IN := resp \ 1 IS THE CORRECT RESPONSE
 resp 1 =
 IF  county 1 + := county 0 := countn \ IF CORRECT....
    1 := ok
    ELSE 0 := county countn 1 + := countn 0 := ok
 THEN                           ;

\ NEXT STIMULUS                   17:58 22.12.98
: NEXTSTIM
 county correct = IF        \ CHANGE DIRECTION
           current 1- := current
           0 := county 0 := countn
           THEN          \
 countn ( correct = ) IF \ CHANGE DIRECTION
           current 1+ := current
           0 := county 0 := countn
           THEN          \
 current -15 MAX := current          \ STOP LOW NUMS
 current 18 MIN := current           \ STOP HIGH NUMS

\ STORE VALUES FOR PROGRAM STATUS          04:47 12/03/96
: STOREVAL
 rms        9994 STORE \ RMS VALUE
 county   FLOAT  9995 STORE \ NUMBER OF CORRECT +VE
 countn   FLOAT  9996 STORE \ NUMBER OF CORRECT -VE
 ok       FLOAT  9997 STORE \ LAST DIRECTION
 current  FLOAT  9998 STORE \ LAST STIMULUS
 resp     FLOAT  9999 STORE \ LAST RESPONSE

\                              13:02 15.01.99
: GO := ifl
 0  := current      \ SET current TO REFERENCE
 0  := county
 0  := countn
 3  := correct      \ SET NUMBER OF CORRECT RESPONSES REQU
 80 := repeats      \ SET NUMBER OF REPEATS
\ SET PARAMETERS TABLE
```

```
 1.0 := 1 PARA
 0.0 := 13 PARA
 0.0 := 12 PARA
 10.0 := 17 PARA
 200.0 := 18 PARA

\                      11:09 15.01.99
\       PARAMETERS
 2.0 := 7 PARA

repeats 1 + 1 DO        \ SET UP LOOP
 CR 17 DEL          \
 CR 18 DEL          \
 ORDER1             \
 STOREVAL
 NEXTSTIM             \
LOOP                \
```

Figure C1-2 Study 1: Absolute thresholds, Method B (Up-down, yes-no), Screenfiles to run threshold test.

```
\                              13:38 05.02.01
\
\ SCREEN TO M1 FILES
\ FOR STUDY 1
\
\      ABSOLUTE THRESHOLDS WITH FORCED-CHOICE
\
\              CREATED BY MIYUKI M
\
\
\ CREATE FILES                     10:40 06.09.99
  97 120 NDEL 0.0 := 13 PARA  1.0 := 11 PARA
: TAPER " TAPER" BRUN COPY END-MODULE ;

\ CREATE PAUSE
  140 DEL

\ CREATE 8 Hz
\ 8.0 := 14 PARA 400.0 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 50 50 TAPER

\ CREATE 16 Hz
  16.0 := 14 PARA 400.0 := 10 PARA 1.0 := 12 PARA 99 SINE
  1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
  99 100 500 500 TAPER

\ CREATE 31.5 Hz                   10:56 03.08.99
\ 31.5 := 14 PARA 700.28 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 100 100 TAPER

\ CREATE 63.0 Hz
\ 63.0 := 14 PARA 1400.56 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 200 200 TAPER

\ CREATE 125.0 Hz
\ 125.0 := 14 PARA 2500.0 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 400 400 TAPER

\ CREATE 250.0 Hz                  13:37 05.02.01
\ 250.0 := 14 PARA 5000.0 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 500 500 TAPER

\ CREATE 500.0 Hz
\ 500.0 := 14 PARA 8064.51 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 1000 1000 TAPER

\ TAPER                            10:41 06.09.99
  99 DEL

\ CREATE LIGHT
  200 201 NDEL
  2.5 := 12 PARA 1.0 := 11 PARA
 -2.5 := 13 PARA  200 SINE

\ CREATE OFF LIGHT
  0.0 := 12 PARA 1.0 := 11 PARA
 -2.5 := 13 PARA 201 SINE

\ CREATE OTHER FILES               16:25 08.12.97

   1.2589 := constant 100 101 FILE*
   1.5849 := constant 100 102 FILE*
   1.9953 := constant 100 103 FILE*
   2.5119 := constant 100 104 FILE*
   3.1623 := constant 100 105 FILE*
   3.9811 := constant 100 106 FILE*
   5.0119 := constant 100 107 FILE*
   6.3096 := constant 100 108 FILE*
   7.9433 := constant 100 109 FILE*
  10.0000 := constant 100 110 FILE*
  12.5893 := constant 100 111 FILE*
  15.8489 := constant 100 112 FILE*

\                                  16:25 08.12.97
  19.9526 := constant 100 113 FILE*
  25.1189 := constant 100 114 FILE*
  31.6228 := constant 100 115 FILE*
  39.8107 := constant 100 116 FILE*
  50.1187 := constant 100 117 FILE*
  63.0957 := constant 100 118 FILE*
   0.0000 := constant 100 120 FILE*
```

Figure C1-3 Study 1: Absolute thresholds, Method C (Up-down, forced-choice), Screenfiles to set up stimuli.

```
\                        13:39 05.02.01
\
\ M2  BATCH JOBS
\ FOR STUDY 1
\
\   ABSOLUTE THRESHOLDS WITH FORCED-CHOICE
\
\              CREATED BY MIYUKI M
\
\ JOB TO PRESENT STIMULI              14:15 08.12.97
\ NEED FILES : 100  = REFERENCE
\ 101 = REF+1, 102 = REF+2, 103 = REF+3, 104 = REF+4, 105 REF+5
\ 106 = REF+6, 107 = REF+7, 108 = REF+8, 109 = REF+9, 110 REF+10
\ 111 = REF+11, 112 = REF+12, 113 = REF+13, 114 = REF+14,
\ 115 = REF+15, 116 = REF+16, 117 = REF+17, 118 = REF+18
\ 120 = NULL FILE, 140 = PAUSE, 200 = LIGHT, 201 = OFF LIGHT

: MODULE ;
: LXTRACT  " LXTRACT"  BRUN COPY  END-MODULE ;
  INTEGER resp INTEGER countn INTEGER dim 1 := dim
  INTEGER current INTEGER ifl INTEGER repeats INTEGER county
  INTEGER correct   INTEGER ok
  REAL rms   REAL value
  VARIABLE VOCVAR VARIABLE DPVAR
        value 1.0 := value
\ ORDER 0                         16:00 02.08.99
: ORDER0
  120 140 ifl current + 3 17 MERGE  \ STIMULUS
  200 201 200 3 18 MERGE        \ LIGHT
  1 DEL  32767 DEL
 ."  DATA DATA DATA " CR              \ RUN DATA
  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  3.0 := 5 PARA   DATA
 ."                  WEBER'S LAW PROGRAM " CR
 ."                  ***** Order 0 ***** " CR
  2.1 0.8 1 32767 LXTRACT
  32767 STATS 5 CB := rms

\                          15:42 12/05/97
 ." TEST FILE : " ifl current + . CR CR
 ." Do you judge the first or second to be perceptible ? "
```

```
  CR 1000 8 BEEP
." Enter 0 or 1 " #IN := resp \ 0 IS THE CORRECT RESPONSE
 resp 0 =
 IF   county 1 + := county 0 := countn   \ IF CORRECT....
     1 := ok
     ELSE 0 := county countn 1 + := countn  0 := ok  THEN ;

\ ORDER 1                            16:00 02.08.99
: ORDER1
  ifl current + 140 120 3 17 MERGE   \ STIMULUS
  200 201 200 3 18 MERGE     \ LIGHT
  1 DEL 32767 DEL
 ."  DATA DATA DATA " CR              \ RUN DATA
  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  3.0 := 5 PARA   DATA
 ."                 WEBER'S LAW PROGRAM " CR
 ."                 ***** Order 1 ***** " CR
  0.1 0.8 1 32767 LXTRACT
  32767 STATS 5 CB := rms

\                                16:51 11/20/97
 ." TEST FILE : " ifl current + . CR CR
 ." Do you judge the first or second to be perceptible ? "
   CR 1000 8 BEEP
 ." Enter 0 or 1 " #IN := resp \ 1 IS THE CORRECT RESPONSE
  resp 1 =
  IF   county 1 + := county 0 := countn \ IF CORRECT....
      1 := ok
      ELSE 0 := county countn 1 + := countn 0 := ok  THEN          ;

\ NEXT STIMULUS                    17:58 22.12.98
: NEXTSTIM
  county correct = IF          \ CHANGE DIRECTION
             current 1- := current
             0 := county 0 := countn
             THEN           \
  countn ( correct = ) IF \ CHANGE DIRECTION
             current 1+ := current
             0 := county 0 := countn             THEN        \
  current -15 MAX := current            \ STOP LOW NUMS
  current 18 MIN := current            \ STOP HIGH NUMS
```

```
\ STORE VALUES FOR PROGRAM STATUS               16:02 03.09.99
: STOREVAL
 rms          8884 STORE \ RMS VALUE
 county   FLOAT  8885 STORE \ NUMBER OF CORRECT +VE
 countn   FLOAT  8886 STORE \ NUMBER OF CORRECT -VE
 ok      FLOAT  8887 STORE \ LAST DIRECTION
 current  FLOAT  8888 STORE \ LAST STIMULUS
 resp     FLOAT  8889 STORE \ LAST RESPONSE
 ;
\                          13:01 15.01.99
: GO := ifl
 0  := current       \ SET current TO REFERENCE
 0  := county
 0  := countn
 3  := correct       \ SET NUMBER OF CORRECT RESPONSES REQU
 80 := repeats        \ SET NUMBER OF REPEATS
88 DEL 0.5 := 12 PARA 0.5 := 13 PARA 88 RANDOM CLS \ SET UP RUN
\ SET PARAMETERS TABLE
   1.0 := 1 PARA    0.0 := 13 PARA
   0.0 := 12 PARA    10.0 := 17 PARA    200.0 := 18 PARA

\                          15:53 12/05/97
\       PARAMETERS
   2.0 := 7 PARA
  repeats 1 + 1 DO          \ SET UP LOOP
   CR 17 DEL    CR 18 DEL            \
   I 88 VALUE FIX          \ RANDOM ORDER
    IF ORDER1  ELSE ORDER0  THEN
    STOREVAL
    NEXTSTIM              \
  LOOP              ;
```

Figure C1-4 Study 1: Absolute thresholds, Method C (Up-down, forced-choice), Screenfiles to run threshold test.

```
\                         13:44 05.02.01
\
\ SCREEN TO CREATE FILES
\   FOR STUDY 3
\
\                 CREATED BY MIYUKI M
\
\ CREATE FILES                    15:37 27.11.98
  99 120 NDEL 0.0 := 13 PARA  3.0 := 11 PARA  10.0 := 17 PARA
: TAPER    " TAPER"  BRUN COPY  END-MODULE ;

\ CREATE PAUSE
  140 DEL
\ CREATE 8 Hz
\ 8.0 := 14 PARA 400.0 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 100 100 TAPER

\ CREATE 16 Hz
\ 16.0 := 14 PARA 400.0 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 100 100 TAPER

\ CREATE 31.5 Hz                  17:25 25.11.98
  31.5 := 14 PARA 700.28 := 10 PARA 0.05 := 12 PARA 99 SINE
  1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
  99 100 150 150 TAPER

\ CREATE 64.0 Hz
\ 64.0 := 14 PARA 1400.56 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 300 300 TAPER

\ CREATE 125.0 Hz
\ 125.0 := 14 PARA 2500.0 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 600 600 TAPER

\ CREATE 250.0 Hz                 15:48 24.11.98
\ 250.0 := 14 PARA 5000.0 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
```

```
\ 99 100 1000 1000 TAPER

\ CREATE 500.0 Hz
\ 500.0 := 14 PARA 8064.51 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 2000 2000 TAPER

\ TAPER                         17:31 05.12.97
  99 DEL

\ CREATE LIGHT
  200 201 NDEL
  2.5 := 12 PARA 3.0 := 11 PARA
  -2.5 := 13 PARA  200 SINE

\ CREATE OFF LIGHT
  0.0 := 12 PARA 1.0 := 11 PARA
  -2.5 := 13 PARA 201 SINE

\ CREATE OTHER FILES                 16:25 08.12.97
    1.2589 := constant 100 101 FILE"
    1.5849 := constant 100 102 FILE"
    1.9953 := constant 100 103 FILE"
    2.5119 := constant 100 104 FILE"
    3.1623 := constant 100 105 FILE"
    3.9811 := constant 100 106 FILE"
    5.0119 := constant 100 107 FILE"
    6.3096 := constant 100 108 FILE"
    7.9433 := constant 100 109 FILE"
   10.0000 := constant 100 110 FILE"
   12.5893 := constant 100 111 FILE"
   15.8489 := constant 100 112 FILE"

\                              16:25 08.12.97
   19.9526 := constant 100 113 FILE"
   25.1189 := constant 100 114 FILE"
   31.6228 := constant 100 115 FILE"
   39.8107 := constant 100 116 FILE"
   50.1187 := constant 100 117 FILE"
   63.0957 := constant 100 118 FILE"
    0.0000 := constant 100 120 FILE"
```

Figure C2-1 Studies 2 and 3: Absolute thresholds, Screenfiles to set up stimuli.

```
\                              13:45 05.02.01

\ BATCH JOBS
\
\  FOR STUDY 3  ABSOLUTE THRESHOLDS
\
\              CREATED BY  MIYUKI M


\ JOB TO PRESENT STIMULI              14:15 08.12.97
\ NEED FILES : 100  = REFERENCE
\ 101 = REF+1, 102 = REF+2, 103 = REF+3, 104 = REF+4, 105 REF+5
\ 106 = REF+6, 107 = REF+7, 108 = REF+8, 109 = REF+9, 110 REF+10
\ 111 = REF+11, 112 = REF+12, 113 = REF+13, 114 = REF+14,
\ 115 = REF+15, 116 = REF+16, 117 = REF+17, 118 = REF+18
\ 120 = NULL FILE, 140 = PAUSE, 200 = LIGHT, 201 = OFF LIGHT

: MODULE ;
: LXTRACT  " LXTRACT"  BRUN COPY  END-MODULE ;
  INTEGER resp INTEGER countn INTEGER dim 1 := dim
  INTEGER current INTEGER ifl INTEGER repeats INTEGER county
  INTEGER correct  INTEGER ok
  REAL rms  REAL value
  VARIABLE VOCVAR VARIABLE DPVAR
        value 1.0 := value
\ ORDER 0                       16:19 23.11.98
: ORDER0
  120 140 ifl current + 3 17 MERGE  \ STIMULUS
  200 201 200 3 18 MERGE       \ LIGHT
  1 DEL  32767 DEL
 ."  DATA DATA DATA " CR            \ RUN DATA

  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  7.0 := 5 PARA  DATA
 ."                WEBER'S LAW PROGRAM " CR
 ."                ***** Order 0 ***** " CR

  4.0 3.0 1 32767 LXTRACT
  32767 STATS 5 CB := rms

\                              15:42 12/05/97

." TEST FILE : " ifl current + . CR CR
." Do you judge the first or second to be perceptible ? "
  CR 1000 8 BEEP
." Enter 0 or 1 " #IN := resp \ 0 IS THE CORRECT RESPONSE
 resp 0 =

 IF  county 1 + := county 0 := countn  \ IF CORRECT....
    1 := ok
    ELSE 0 := county countn 1 + := countn  0 := ok  THEN ;

\ ORDER 1                          16:19 23.11.98
: ORDER1
  ifl current + 140 120 3 17 MERGE  \ STIMULUS
  200 201 200 3 18 MERGE   \ LIGHT
  1 DEL 32767 DEL
 ."  DATA DATA DATA " CR            \ RUN DATA
  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  7.0 := 5 PARA  DATA
 ."                WEBER'S LAW PROGRAM " CR
 ."                ***** Order 1 ***** " CR
  0.0 3.0 1 32767 LXTRACT
  32767 STATS 5 CB := rms

\                              16:51 11/20/97
 ." TEST FILE : " ifl current + . CR CR
 ." Do you judge the first or second to be perceptible ? "
   CR 1000 8 BEEP
 ." Enter 0 or 1 " #IN := resp \ 1 IS THE CORRECT RESPONSE
  resp 1 =
  IF  county 1 + := county 0 := countn \ IF CORRECT....
     1 := ok
     ELSE 0 := county countn 1 + := countn 0 := ok  THEN            ;

\ NEXT STIMULUS                        16:20 23.11.98
: NEXTSTIM
  county correct = IF        \ CHANGE DIRECTION
            current 1- := current
            0 := county 0 := countn
            THEN           \

countn ( correct = ) IF \ CHANGE DIRECTION
          current 1+ := current
          0 := county 0 := countn
          THEN         \
 current -3 MAX := current         \ STOP LOW NUMS
 current 18 MIN := current         \ STOP HIGH NUMS

\ STORE VALUES FOR PROGRAM STATUS          04:47 12/03/96
: STOREVAL
 rms        9994 STORE \ RMS VALUE
 county   FLOAT  9995 STORE \ NUMBER OF CORRECT +VE
 countn   FLOAT  9996 STORE \ NUMBER OF CORRECT -VE
 ok      FLOAT  9997 STORE \ LAST DIRECTION
 current  FLOAT  9998 STORE \ LAST STIMULUS
 resp    FLOAT  9999 STORE \ LAST RESPONSE
 ;
\                              14:14 08.12.97
: GO := ifl
 0  := current       \ SET current TO REFERENCE
 0  := county
 0  := countn
 3  := correct       \ SET NUMBER OF CORRECT RESPONSES REQU
 80 := repeats       \ SET NUMBER OF REPEATS
 88 DEL 0.5 := 12 PARA 0.5 := 13 PARA 88 RANDOM CLS \ SET UP RAN
 \ SET PARAMETERS TABLE
   1.0 := 1 PARA
   0.0 := 13 PARA
   0.0 := 12 PARA

\                              15:53 12/05/97
\       PARAMETERS
   2.0 := 7 PARA

 repeats 1 + 1 DO        \ SET UP LOOP
   CR 17 DEL          \
   CR 18 DEL          \
   I 88 VALUE FIX        \ RANDOM ORDER
   IF ORDER1  ELSE ORDER0  THEN
   STOREVAL
   NEXTSTIM           \
 LOOP        ;      \
```

Figure C2-2 Studies 2 and 3: Absolute thresholds, Screenfiles to run a threshold test (up-down, forced-choice)

```
\                                  13:51 05.02.01
\
\ "LSET" TO SCREEN FILES
\\ FOR STUDY 5
\
\  SENSATION LOCALISATIN TEST
\
\                              CREATED BY MIYUKI M
\                                  AT 17/11/99
\
\ CREATE FILES                          10:08 12/03/99
 90 99 NDEL 201 205 NDEL 401 405 NDEL 501 505 NDEL
 222 DEL
: TAPER    " TAPER" BRUN COPY  END-MODULE ;

\ SET STIMULUS PARAMETERS
 5000.0 := 10 PARA
 5.0 := 11 PARA
 0.0 := 13 PARA

\ SET FREQUENCY
  8.0 := 14 PARA 0.133 := 12 PARA 90 SINE
 16.0 := 14 PARA 0.053 := 12 PARA 91 SINE
 31.5 := 14 PARA 0.027 := 12 PARA 92 SINE
 63.0 := 14 PARA 0.02 := 12 PARA 93 SINE
 125.0 := 14 PARA 0.0185 := 12 PARA 94 SINE

\ CREATE TEST STIMULI                        11:26 11/19/99
 90 95 500 500 TAPER \ 8 Hz
 91 96 500 500 TAPER \ 16 Hz
 92 97 500 500 TAPER \ 31.5 Hz
 93 98 500 500 TAPER \ 63 Hz
 94 99 500 500 TAPER \ 125 Hz

\ CREATE LIGHT
 5.0 := 11 PARA 125.0 := 14 PARA
 2.5 := 12 PARA -2.5 := 13 PARA 222 SINE
```

```
\ CREATE STIMULUS MAGNITUDE                11:27 11/19/99
 2.0 := constant 95 201 FILE" \ 8
 4.0 := constant 95 401 FILE" \ 8
\ 4.0 := constant 95 501 FILE" \ 8
 2.0 := constant 96 202 FILE" \ 16
 4.0 := constant 96 402 FILE" \ 16
\ 4.0 := constant 96 502 FILE" \ 16
 2.0 := constant 97 203 FILE" \ 31.5
 4.0 := constant 97 403 FILE" \ 31.5
\ 4.0 := constant 97 503 FILE" \ 31.5
 2.0 := constant 98 204 FILE" \ 63
 4.0 := constant 98 404 FILE" \ 63
\ 4.0 := constant 98 504 FILE" \ 63
 2.0 := constant 99 205 FILE" \ 125
 4.0 := constant 99 405 FILE" \ 125
\ 4.0 := constant 99 505 FILE" \ 125
```

Figure C3-1 Study 5: Sensation localisation test. Screenfiles to set up stimuli.

```
\                               13:52 05.02.01
\ "LJOB" BATCH JOBS
\\ FOR STUDY 5
\
\ SENSATION LOCALISATION TEST
\
\                          CREATED BY MIYUKI M
\                               AT 17/11/99
\
\ JOB TO PRESENT STIMULI                  11:01 11/19/99
\ NEED FILES
\ 101, 102 = 8 Hz stimuli
\ 201, 202 = 16 Hz stimuli
\ 301, 302 = 31.5 Hz stimuli
\ 401, 402 = 63 Hz stimuli
\ 501, 502 = 125 Hz stimuli
\ 222 = LIGHT
 INTEGER tfile INTEGER current INTEGER repeats INTEGER resp
 INTEGER countr REAL rms REAL value
 VARIABLE VOCVAR VARIABLE DPVAR
    value 1.0 := value
: LXTRACT  " LXTRACT"  BRUN COPY  END-MODULE ;

\ PRESENT STIMULI                   12:10 11/17/99
: PRESENT
 tfile current + 17 COPY       \ TEST STIMULUS
 222 18 COPY                 \ LIGHT
 1 DEL 32767 DEL
 17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
 5.0 := 5 PARA
 DATA

\                               13:07 11/29/99
 0.5 4.0 1 32767 LXTRACT
 32767 STATS 5 CB := rms

 CLS CR CR CR CR 1000 8 BEEP
."   *************** " CR
."   TEST ORDER : " current 1 + . CR
."   *************** " CR CR
."             RMS VALUE --> " rms F. CR CR CR

." Enter LOCATION NUMBER GIVEN by the subject. "
 CR CR
." NUMBER or 0 = REPEAT --> " #IN := resp
      ;

\ NEXT STIMULI                         13:06 11/29/99
: NEXTSTIM
 resp 0 =
 IF   countr 1 + := countr        \ if subject didn't ...
    current := current
 ELSE current 1 + := current      \ if subject judged ...
    0 := countr  THEN ;

\ STORE VALUES                         11:38 11/19/99
: STOREVAL
 current 1 +     FLOAT 3333 STORE \ test order
 rms                  3334 STORE \ test rms value
 resp            FLOAT 3335 STORE \ subject response
 ;

\ MAIN PROGRAM                         09:29 11/18/99
: GO
          5 ?DEPTH     \ enter 5 files
        61 65 NDEL     \ delete 81 85 files
           65 COPY     \ copy 5th file to 85 file
           64 COPY     \ copy 4th file to 82 file
           63 COPY     \ copy 3rd file to 83 file
           62 COPY     \ copy 2nd file to 82 file
           61 COPY     \ copy 1st file to 81 file
           61 := tfile

\ SET NUMBERS                          09:32 11/17/99
 0 := current
 0 := countr
 25 := repeats

\ SET PARAMETERS TABLE
 1.0 := 1 PARA
 2.0 := 7 PARA
 0.0 := 12 PARA
 0.0 := 13 PARA
 4.0 := 17 PARA
 200.0 := 18 PARA

\ MAIN PROGRAM                         13:02 11/29/99
 repeats 1 + 1 DO
  CR 17 DEL
  CR 18 DEL
  PRESENT
  STOREVAL
  NEXTSTIM
  current 4 > IF ABORT ABORT THEN
 LOOP ;
```

Figure C4-2 Study 5: Sensation localisation test. Screenfiles to run a location judgement test.

```
\                                         13:52 05.02.01
\ "MSET" TO SCREEN FILES
\
\ FOR STUDY 6
\
\  SENSATION MAGNITUDE TEST
\
\                    CREATED BY MIYUKI M
\                         AT 17/11/99
\
\ CREATE FILES                     10:11 12/03/99
 90 99 NDEL 201 205 NDEL 401 405 NDEL 501 505 NDEL
 111 DEL 222 DEL 333 DEL
: TAPER    " TAPER" BRUN COPY  END-MODULE ;

\ SET STIMULUS PARAMETERS
 5000.0 := 10 PARA
 2.0 := 11 PARA
 0.0 := 13 PARA

\ SET FREQUENCY
  8.0 := 14 PARA 0.133 := 12 PARA 90 SINE
 16.0 := 14 PARA 0.053 := 12 PARA 91 SINE
 31.5 := 14 PARA 0.027 := 12 PARA 92 SINE
 63.0 := 14 PARA 0.02 := 12 PARA 93 SINE
 125.0 := 14 PARA 0.0185 := 12 PARA 94 SINE
\ CREATE TEST STIMULI                   11:20 11/19/99
 90 95 500 500 TAPER \ 8 Hz
 91 96 500 500 TAPER \ 16 Hz
 92 97 500 500 TAPER \ 31.5 Hz
 93 98 500 500 TAPER \ 63 Hz
 94 99 500 500 TAPER \ 125 Hz

\ CREATE LIGHT
 2.0 := 11 PARA 125.0 := 14 PARA
 2.5 := 12 PARA -2.5 := 13 PARA 222 SINE

\ CREATE OFF LIGHT
 1.0 := 11 PARA 0.0 := 12 PARA
 -2.5 := 13 PARA 333 SINE

\ CREATE STIMULUS MAGNITUDE                11:22 11/19/99
 2.0 := constant 95 201 FILE" \ 8
 4.0 := constant 95 401 FILE" \ 8
\ 4.0 := constant 95 501 FILE" \ 8
 2.0 := constant 96 202 FILE" \ 16
 4.0 := constant 96 402 FILE" \ 16
\ 4.0 := constant 96 502 FILE" \ 16
 2.0 := constant 97 203 FILE" \ 31.5
 4.0 := constant 97 403 FILE" \ 31.5
\ 4.0 := constant 97 503 FILE" \ 31.5
 2.0 := constant 98 204 FILE" \ 63
 4.0 := constant 98 404 FILE" \ 63
\ 4.0 := constant 98 504 FILE" \ 63
 2.0 := constant 99 205 FILE" \ 125
 4.0 := constant 99 405 FILE" \ 125
\ 4.0 := constant 99 505 FILE" \ 125
\ CREATE PAUSE                          09:42 11/17/99
 1.0 := 11 PARA
 0.0 := 12 PARA
 0.0 := 13 PARA  111 SINE
```

Figure C4-1 Study 6: Sensation magnitude: Screenfiles to set up stimuli for the frequency comparison test and the contact

```
\                               13:53 05.02.01
\ "MJOB" BATCH JOBS
\
\ FOR STUDY 6
\  SENSATION MAGNITUDE TEST
\
\                    CREATED BY MIYUKI M
\                         AT 17/11/99
\
\
\ JOB TO PRESENT STIMULI                12:53 11/29/99
\ NEED FILES
\ 101, 102 = 8 Hz stimuli
\ 201, 202 = 16 Hz stimuli
\ 301, 302 = 31.5 Hz stimuli
\ 401, 402 = 63 Hz stimuli
\ 501, 502 = 125 Hz stimuli
\ 111 = PAUSE, 222 = ON LIGHT, 333 = OFF LIGHT
  INTEGER tfile INTEGER current INTEGER repeats INTEGER resp
  INTEGER rfile INTEGER countr REAL rrms REAL trms REAL value
     value 1.0 := value

: LXTRACT   " LXTRACT"   BRUN COPY  END-MODULE ;

\ PRESENT STIMULI                 12:54 11/29/99
: PRESENT
  rfile 111 tfile current + 3 17 MERGE      \ TEST STIMULUS
  222 333 222 3 18 MERGE                    \ LIGHT
  1 DEL 23232 DEL 24242 DEL
  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  5.0 := 5 PARA
  DATA

\                               17:58 12/02/99
  0.5 1.0 1 23232 LXTRACT        \ extract reference
  3.5 1.0 1 24242 LXTRACT        \ extract test
  23232 STATS 5 CB := rrms        \ store reference value
  24242 STATS 5 CB := trms        \ store reference value

  CLS CR CR CR CR 1000 8 BEEP
 ." *************** " CR
." TEST ORDER : " current 1 + . CR
." ************** " CR CR
."              REFERENCE  VALUE --> " rrms F. CR
."              TEST      VALUE --> " trms F. CR CR CR
." Enter MAGNITUDE NUMBER given by the subject " CR CR
." NUMBER or 0 = REPEAT --> " #IN := resp
    ;

\ NEXT STIMULI                      13:03 11/29/99
: NEXTSTIM
 resp 0 =
 IF   countr 1 + := countr       \ if subject didn't ...
      current := current
 ELSE current 1 + := current      \ if subject judged ...
      0 := countr
 THEN  ;

\ STORE VALUES                      11:10 11/19/99
: STOREVAL
 current 1 +    FLOAT 4444 STORE \ order number
 trms               4445 STORE \ test rms value
 rrms               4446 STORE \ reference rms value
 resp           FLOAT 4447 STORE \ subject response
  ;

\ MAIN PROGRAM                      11:17 11/19/99
: GO
         5 ?DEPTH     \ enter 5 files
       81 85 NDEL     \ delete 81 85 files
          85 COPY     \ copy 5th file to 85 file
          84 COPY     \ copy 4th file to 82 file
          83 COPY     \ copy 3rd file to 83 file
          82 COPY     \ copy 2nd file to 82 file
          81 COPY     \ copy 1st file to 81 file
          81 := tfile

 ."   ******************** " CR
 ."   ENTER REFERENCE FILE " CR
 ."   203 OR 403 ? " #IN := rfile
\ SET NUMBERS                       11:10 11/17/99
 0 := current
 0 := countr
 25 := repeats

\ SET PARAMETERS TABLE
 1.0 := 1 PARA
 2.0 := 7 PARA
 0.0 := 12 PARA
 0.0 := 13 PARA
 4.0 := 17 PARA
 200.0 := 18 PARA

\ MAIN PROGRAM                      13:02 11/29/99
 repeats 1 + 1 DO
   CR 17 DEL
   CR 18 DEL
   PRESENT
   STOREVAL
   NEXTSTIM
   current 4 > IF ABORT ABORT THEN
 LOOP
   ;
```

Figure C4-2 Study 6: Sensation magnitude: Screenfiles to run a frequency comparison test.

```
\                              13:54 05.02.01
\ "MJOB3" BATCH JOBS
\
\ FOR STUDY 6
\
\  SENSATION MAGNITUDE TEST
\  CONTACT COMPARISON VERSION
\
\                    CREATED BY MIYUKI M
\                         AT 14/11/99
\                    MODIFIED AT 2/12/99
\
\ JOB TO PRESENT STIMULI                 12:23 11/29/99

\ NEED FILES
\ 101, 102 = 8 Hz stimuli
\ 201, 202 = 16 Hz stimuli
\ 301, 302 = 31.5 Hz stimuli
\ 401, 402 = 63 Hz stimuli
\ 501, 502 = 125 Hz stimuli
\ 111 = PAUSE, 222 = ON LIGHT, 333 = OFF LIGHT
  INTEGER tfile INTEGER current INTEGER repeats INTEGER resp
  INTEGER rfile INTEGER ordern REAL rms REAL value
  INTEGER trepeat INTEGER rrepeat
     value 1.0 := value
: LXTRACT  " LXTRACT"  BRUN COPY  END-MODULE ;

\ WARNING MESSAGE                 17:11 12/02/99
: WARNREF
  CLS CR CR CR CR CR CR
 ."  WARNING !! " CR
 ."  ********** " CR
 ." Ready for the REFERENCE condition " KEY 89 = IF    THEN ;
: WARNNEXT
  CLS CR CR CR CR CR CR
 ."  WARNING !! " CR
 ."  ********** " CR
 ." Ready for the NEXT STIMULUS condition " KEY 89 = IF    THEN ;

\ PRESENT STIMULI                 14:20 11/24/99
: PRESENT
tfile current + 17 COPY        \ TEST STIMULUS
222 18 COPY                  \ LIGHT
1 DEL 23232 DEL
17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
2.0 := 5 PARA  DATA

\                               17:57 12/02/99
 0.5 1.0 1 23232 LXTRACT         \ extract reference
 23232 STATS 5 CB := rms         \ store reference value
 CLS CR CR CR CR 1000 8 BEEP
." ************** -------------------- "       CR
." TEST ORDER : " ordern . ." RMS VALUE : " rms F.  CR
." ************** -------------------- "       CR
 CR CR CR
." Enter MAGNITUDE NUMBER given by the subject " CR CR
." NUMBER or 0 = REPEAT  --> "
 #IN := resp
   ;

\ REFERENCE STIMULI                    14:33 11/24/99
: REFERENCE
 rfile 17 COPY               \ TEST STIMULUS
 222 18 COPY                  \ LIGHT
 1 DEL 23232 DEL
 17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
 2.0 := 5 PARA  DATA

\                               17:52 12/02/99
  0.5 1.0 1 23232 LXTRACT         \ extract reference
  23232 STATS 5 CB := rms         \ store reference value
  CLS CR CR CR CR CR 1000 8 BEEP
 ." ********************** --------------------- " CR
 ." TEST ORDER : REFERENCE   RMS VALUE : " rms F.   CR
 ." ********************** --------------------- " CR
  CR CR CR
 ." PLEASE MAKE SURE THIS STIMULI IS ALLOCATED AT 100 " CR CR
 ." 0 = REPEAT or 1 = NEXT STIMULI ? " #IN := resp
     ;
\ NEXT STIMULI FOR REF STIMULUS                  17:52 12/02/99
: NEXTSTIM1
 resp 0 = IF                  \ repeat reference
     current := current    0 := ordern
     1 := rrepeat   THEN
 resp 1 = IF                  \ go to next stimulus
     current := current  current 1+ := ordern
     0 := rrepeat
 WARNNEXT  THEN ;

\ NEXT STIMULI 2 FOR TEST STIMULUS               09:27 12/03/99
: NEXTSTIM2
 resp 0 = IF                  \ repeat test stimulus
     current := current  current 1+ := ordern
     1 := trepeat
 ELSE                         \ go to reference stimulus
     current 1+ := current  0 := ordern
     0 := trepeat
 WARNREF  THEN ;

\ STORE VALUES                           09:12 12/03/99
: STOREVAL
 ordern       FLOAT 5555 STORE \ order number
 rms               5556 STORE \ rms value
 resp         FLOAT 5557 STORE \ subject response
  ;

\ MAIN PROGRAM                           15:24 11/24/99
: GO
          4 ?DEPTH    \ enter 5 files
       81 84 NDEL     \ delete 81 85 files
          84 COPY     \ copy 4th file to 83 file
          83 COPY     \ copy 3rd file to 83 file
          82 COPY     \ copy 2nd file to 82 file
          81 COPY     \ copy 1st file to 81 file
          81 := tfile                          .

 ."  ******************** " CR
 ."  ENTER REFERENCE FILE " CR
 ."  203 OR 403 ? " #IN := rfile
```

Figure C4-3 Study 6: Sensation magnitude, Screenfiles to run a contact comparison test.

```
\ SET NUMBERS                    12:24 11/29/99

 0 := current
 0 := trepeat
 0 := rrepeat
 0 := ordern

\ SET PARAMETERS TABLE
 1.0 := 1 PARA
 2.0 := 7 PARA
 0.0 := 12 PARA
 0.0 := 13 PARA
 4.0 := 17 PARA
 200.0 := 18 PARA

\ MAIN PROGRAM                   11:20 12/02/99

 repeats 1 + 1 DO
  BEGIN
   CR 17 DEL CR 18 DEL
   REFERENCE STOREVAL NEXTSTIM1
   rrepeat 1 = WHILE REPEAT
  BEGIN
   CR 17 DEL CR 18 DEL
   PRESENT STOREVAL NEXTSTIM2
   trepeat 1 = WHILE REPEAT
   current 3 > IF ABORT ABORT THEN
  LOOP
    ;
```

Figure C4-4 Study 6: Sensation magnitude, Screenfiles to run a contact comparison test. –Cont.

```
\                                   14:01 05.02.01
\
\ SCREEN TO DL (LOW MAGNITUDE) FILES
\ FOR STUDY 7
\
\            CREATED BY MIYUKI M
\
\
\ CREATE FILES                    17:15 06.07.98
  99 120 NDEL 140 DEL 0.0 := 13 PARA  3.0 := 11 PARA
  10.0 := 17 PARA 600.0 := 18 PARA 1.0 := 7 PARA
: TAPER    " TAPER" BRUN COPY  END-MODULE ;

\ CREATE 8 Hz
\ 8.0 := 14 PARA 400.0 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 100 100 TAPER

\ CREATE 16 Hz
  16.0 := 14 PARA 400.0 := 10 PARA 0.05 := 12 PARA 99 SINE
  1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
  99 100 100 100 TAPER

\ CREATE 31.5 Hz                  12:34 03.07.98
\ 31.5 := 14 PARA 700.28 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 150 150 TAPER

\ CREATE 63.0 Hz
\ 64.0 := 14 PARA 1400.56 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 300 300 TAPER

\ CREATE 125.0 Hz
\ 125.0 := 14 PARA 2500.0 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 600 600 TAPER

\ CREATE 250.0 Hz                 17:15 06.07.98
\ 250.0 := 14 PARA 5000.0 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 1000 1000 TAPER

\ CREATE 500.0 Hz
\ 500.0 := 14 PARA 8064.51 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 2000 2000 TAPER
```

```
\ TAPER                          17:31 05.12.97
  99 DEL

\ CREATE LIGHT
  200 201 NDEL
  2.5 := 12 PARA 3.0 := 11 PARA
  -2.5 := 13 PARA  200 SINE

\ CREATE OFF LIGHT
  0.0 := 12 PARA 1.0 := 11 PARA
  -2.5 := 13 PARA 201 SINE

\ CREATE OTHER FILES                 13:34 22.06.98
    1.0292 := constant 100 101 FILE*
    1.0593 := constant 100 102 FILE*
    1.0902 := constant 100 103 FILE*
    1.1220 := constant 100 104 FILE*
    1.1548 := constant 100 105 FILE*
    1.1885 := constant 100 106 FILE*
    1.2232 := constant 100 107 FILE*
    1.2589 := constant 100 108 FILE*
    1.2957 := constant 100 109 FILE*
    1.3335 := constant 100 110 FILE*
    1.3725 := constant 100 111 FILE*
    1.4125 := constant 100 112 FILE*

\                               10:38 25.06.98
    1.4538 := constant 100 113 FILE*
    1.4962 := constant 100 114 FILE*
    1.5399 := constant 100 115 FILE*
    1.5849 := constant 100 116 FILE*
    1.6312 := constant 100 117 FILE*
    1.6788 := constant 100 118 FILE*
```

Figure C5-1 Study 7: Difference threshold, Screenfiles to set up stimuli (low magnitude at 2.0 ms^{-2} r.m.s.

```
\                    14:00 05.02.01
\ SCREEN TO DL (HIGH MAGNITUDE) FILES
\ FOR STUDY 7
\
\          CREATED BY MIYUKI M
\
\
\ CREATE FILES                    12:48 03.07.98
  99 120 NDEL 140 DEL 0.0 := 13 PARA  3.0 := 11 PARA
  10.0 := 17 PARA 600.0 := 18 PARA 1.0 := 7 PARA
: TAPER    " TAPER" BRUN COPY  END-MODULE ;

\ CREATE 8 Hz
\ 8.0 := 14 PARA 400.0 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 100 100 TAPER

\ CREATE 16 Hz
\ 16.0 := 14 PARA 400.0 := 10 PARA 0.5 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 100 100 TAPER

\ CREATE 31.5 Hz                  17:06 06.07.98
\ 31.5 := 14 PARA 700.28 := 10 PARA 0.5 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 150 150 TAPER

\ CREATE 63.0 Hz
\ 64.0 := 14 PARA 1400.56 := 10 PARA 0.5 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 300 300 TAPER

\ CREATE 125.0 Hz
  125.0 := 14 PARA 2500.0 := 10 PARA 0.5 := 12 PARA 99 SINE
  1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
  99 100 600 600 TAPER

\ CREATE 250.0 Hz                 17:06 06.07.98
\ 250.0 := 14 PARA 5000.0 := 10 PARA 0.5 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 1000 1000 TAPER

\ CREATE 500.0 Hz
\ 500.0 := 14 PARA 8064.51 := 10 PARA 0.5 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 2000 2000 TAPER


\ TAPER                           17:31 05.12.97
 99 DEL

\ CREATE LIGHT
 200 201 NDEL
 2.5 := 12 PARA 3.0 := 11 PARA
 -2.5 := 13 PARA  200 SINE

\ CREATE OFF LIGHT
 0.0 := 12 PARA 1.0 := 11 PARA
 -2.5 := 13 PARA 201 SINE

\ CREATE OTHER FILES              13:34 22.06.98
   1.0292 := constant 100 101 FILE*
   1.0593 := constant 100 102 FILE*
   1.0902 := constant 100 103 FILE*
   1.1220 := constant 100 104 FILE*
   1.1548 := constant 100 105 FILE*
   1.1885 := constant 100 106 FILE*
   1.2232 := constant 100 107 FILE*
   1.2589 := constant 100 108 FILE*
   1.2957 := constant 100 109 FILE*
   1.3335 := constant 100 110 FILE*
   1.3725 := constant 100 111 FILE*
   1.4125 := constant 100 112 FILE*

\                                 10:38 25.06.98
  1.4538 := constant 100 113 FILE*
  1.4962 := constant 100 114 FILE*
  1.5399 := constant 100 115 FILE*
  1.5849 := constant 100 116 FILE*
  1.6312 := constant 100 117 FILE*
  1.6788 := constant 100 118 FILE*
```

Figure C5-2 Study 7: Difference threshold, Screenfiles to set up stimuli (high magnitude at 4.0 ms^{-2} r.m.s.

```
\                               14:04 05.02.01
\ DL   BATCH JOBS
\
\   DIFFERENCE THRESHOLDS
\   FOR STUDY 7
\
\            CREATED BY MIYUKI M
\

\ JOB TO PRESENT STIMULI                12:21 22.06.98
\ NEED FILES : 100  = REFERENCE
\ 101 = REF+1, 102 = REF+2, 103 = REF+3, 104 = REF+4, 105 REF+5
\ 106 = REF+6, 107 = REF+7, 108 = REF+8, 109 = REF+9, 110 REF+10
\ 111 = REF+11, 112 = REF+12, 113 = REF+13, 114 = REF+14,
\ 115 = REF+15, 116 = REF+16, 117 = REF+17, 118 = REF+18
\ 140 = PAUSE, 200 = LIGHT, 201 = OFF LIGHT

: MODULE ;
: LXTRACT  " LXTRACT"  BRUN COPY  END-MODULE ;
  INTEGER resp INTEGER countn INTEGER dim 1 := dim
  INTEGER current INTEGER ifl INTEGER repeats INTEGER county
  INTEGER correct  INTEGER ok
  REAL rms REAL rms2  REAL value
  VARIABLE VOCVAR VARIABLE DPVAR
         value 1.0 := value

\ ORDER 0                        17:01 09.07.98
: ORDER0
  100 140 ifl current + 3 17 MERGE   \ STIMULUS
  200 201 200 3 18 MERGE        \ LIGHT
  1 DEL 32767 DEL 23434 DEL
 ."  DATA DATA DATA " CR              \ RUN DATA
  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  5.0 := 5 PARA   DATA
 ."                   WEBER'S LAW PROGRAM " CR
 ."                   ***** Order 0 ***** " CR

\                               17:01 09.07.98
  0.0 2.0 1 23434 LXTRACT
  23434 STATS 5 CB := rms2
  3.0 2.0 1 32767 LXTRACT
 32767 STATS 5 CB := rms
." TEST FILE : " ifl current + . CR CR
." Do you judge the first or second to be greater ? "
  CR 1000 8 BEEP
." Enter 0 or 1 " #IN := resp \ 0 IS THE CORRECT RESPONSE
 resp 0 =
 IF   county 1 + := county 0 := countn   \ IF CORRECT....
     1 := ok
     ELSE 0 := county countn 1 + := countn  0 := ok  THEN ;

\ ORDER 1                                17:01 09.07.98
: ORDER1
  ifl current + 140 100 3 17 MERGE   \ STIMULUS
  200 201 200 3 18 MERGE     \ LIGHT
  1 DEL 32767 DEL 23434 DEL
 ."  DATA DATA DATA " CR              \ RUN DATA
  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  5.0 := 5 PARA   DATA
 ."                   WEBER'S LAW PROGRAM " CR
 ."                   ***** Order 1 ***** " CR

\                               17:01 09.07.98
  0.0 2.0 1 32767 LXTRACT
  32767 STATS 5 CB := rms
  3.0 2.0 1 23434 LXTRACT
  23434 STATS 5 CB := rms2
 ." TEST FILE : " ifl current + . CR CR
 ." Do you judge the first or second to be greater ?"
   CR 1000 8 BEEP
 ." Enter 0 or 1 " #IN := resp \ 1 IS THE CORRECT RESPONSE
  resp 1 =
  IF   county 1 + := county 0 := countn \ IF CORRECT....
      1 := ok
      ELSE 0 := county countn 1 + := countn 0 := ok  THEN    ;

\ NEXT STIMULUS                          18:07 02.07.98
: NEXTSTIM
  county correct = IF          \ CHANGE DIRECTION
              current 1- := current
              0 := county 0 := countn    THEN      \
  countn ( correct = ) IF \ CHANGE DIRECTION
           current 1+ := current
           0 := county 0 := countn
           THEN           \
 current -10 MAX := current             \ STOP LOW NUMS
 current 18 MIN := current             \ STOP HIGH NUMS
           ;

\ STORE VALUES FOR PROGRAM STATUS               12:32 22.06.98
: STOREVAL
  rms           9993 STORE \ test VALUE
  rms2           9994 STORE \ ref VALUE
  county    FLOAT  9995 STORE \ NUMBER OF CORRECT +VE
  countn    FLOAT  9996 STORE \ NUMBER OF CORRECT -VE
  ok       FLOAT  9997 STORE \ LAST DIRECTION
  current   FLOAT  9998 STORE \ LAST STIMULUS
  resp      FLOAT  9999 STORE \ LAST RESPONSE
  ;

\                               17:02 09.07.98
: GO := ifl
  0  := current        \ SET current TO REFERENCE
  0  := county
  0  := countn
  3  := correct        \ SET NUMBER OF CORRECT RESPONSES REQU
  80 := repeats        \ SET NUMBER OF REPEATS
 88 DEL 0.5 := 12 PARA 0.5 := 13 PARA 88 RANDOM CLS \ SET UP RAN
 \ SET PARAMETERS TABLE
    1.0 := 1 PARA    0.0 := 13 PARA
    0.0 := 12 PARA   10.0 := 17 PARA
    1000.0 := 18 PARA

\                               15:53 12/05/97

\         PARAMETERS
    2.0 := 7 PARA
  repeats 1 + 1 DO           \ SET UP LOOP   .
   CR 17 DEL   CR 18 DEL            \
   I 88 VALUE FIX            \ RANDOM ORDER
    IF ORDER1  ELSE ORDER0  THEN
    STOREVAL    NEXTSTIM                 \
  LOOP              ;    \
```

Figure C5-3 Study 7: Difference threshold, Screenfiles to run a test.

```
\
\ SCREEN TO MT1 FILES
\ FOR STUDY 8
\
\       ABSOLUTE  THRESHOLDS  OF  TEST  STIMULI  WITH
FORCED-CHOICE
\
\                 CREATED BY MIYUKI M
\
\
\ CREATE FILES                          14:46 30.09.99
  97 120 NDEL 0.0 := 13 PARA  0.6 := 11 PARA
: TAPER " TAPER" BRUN COPY END-MODULE ;

\ CREATE PAUSE
 140 DEL

\ CREATE 8 Hz
\ 8.0 := 14 PARA 400.0 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 50 50 TAPER

\ CREATE 16 Hz
\ 16.0 := 14 PARA 5000.0 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 0.6 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 500 500 TAPER
\ CREATE 31.5 Hz                        14:46 30.09.99
\ 31.5 := 14 PARA 700.28 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 100 100 TAPER

\ CREATE 63.0 Hz
\ 63.0 := 14 PARA 1400.56 := 10 PARA 0.1 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 200 200 TAPER

\ CREATE 125.0 Hz
 125.0 := 14 PARA 5000.0 := 10 PARA 0.01 := 12 PARA 99 SINE
 0.6 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
 99 100 313 313 TAPER


\ CREATE 250.0 Hz                       18:57 04.09.99
\ 250.0 := 14 PARA 5000.0 := 10 PARA 0.05 := 12 PARA 99 SINE
\ 1.0 := 11 PARA 0.0 := 12 PARA 0.0 := 13 PARA 140 SINE
\ 99 100 700 700 TAPER

\ TAPER                                 09:54 06.09.99
 99 DEL

\ CREATE LIGHT
 200 201 NDEL
 2.5 := 12 PARA 0.6 := 11 PARA 250.0 := 14 PARA
 -2.5 := 13 PARA  200 SINE

\ CREATE OFF LIGHT
 0.0 := 12 PARA 0.6 := 11 PARA
 -2.5 := 13 PARA 201 SINE

\ CREATE OTHER FILES                    16:25 08.12.97
   1.2589 := constant 100 101 FILE*
   1.5849 := constant 100 102 FILE*
   1.9953 := constant 100 103 FILE*
   2.5119 := constant 100 104 FILE*
   3.1623 := constant 100 105 FILE*
   3.9811 := constant 100 106 FILE*
   5.0119 := constant 100 107 FILE*
   6.3096 := constant 100 108 FILE*
   7.9433 := constant 100 109 FILE*
  10.0000 := constant 100 110 FILE*
  12.5893 := constant 100 111 FILE*
  15.8489 := constant 100 112 FILE*

\                                       16:25 08.12.97
  19.9526 := constant 100 113 FILE*
  25.1189 := constant 100 114 FILE*
  31.6228 := constant 100 115 FILE*
  39.8107 := constant 100 116 FILE*
  50.1187 := constant 100 117 FILE*
  63.0957 := constant 100 118 FILE*
   0.0000 := constant 100 120 FILE*
```

Figure C6-1 Study 8: Masked thresholds, scrreenfiles to set up test stimuli.

```
\                                 14:11 05.02.01
\ MT2 BATCH JOBS
\ FOR STUDY 8
\   ABSOLUTE THRESHOLDS OF TEST STIMULI WITH FORCED-CHOICE
\
\           CREATED BY MIYUKI M
\
\ JOB TO PRESENT STIMULI          14:15 08.12.97
\ NEED FILES : 100  = REFERENCE
\ 101 = REF+1, 102 = REF+2, 103 = REF+3, 104 = REF+4, 105 REF+5
\ 106 = REF+6, 107 = REF+7, 108 = REF+8, 109 = REF+9, 110 REF+10
\ 111 = REF+11, 112 = REF+12, 113 = REF+13, 114 = REF+14,
\ 115 = REF+15, 116 = REF+16, 117 = REF+17, 118 = REF+18
\ 120 = NULL FILE, 140 = PAUSE, 200 = LIGHT, 201 = OFF LIGHT

: MODULE ;
: LXTRACT  " LXTRACT"  BRUN COPY  END-MODULE ;
  INTEGER resp INTEGER countn INTEGER dim 1 := dim
  INTEGER current INTEGER ifl INTEGER repeats INTEGER county
  INTEGER correct   INTEGER ok
  REAL rms   REAL value
  VARIABLE VOCVAR VARIABLE DPVAR
        value 1.0 := value
\ ORDER 0                     09:55 06.09.99
: ORDER0
  120 140 ifl current + 3 17 MERGE   \ STIMULUS
  200 201 200 3 18 MERGE        \ LIGHT
  1 DEL  32767 DEL
 ."  DATA DATA DATA " CR            \ RUN DATA
  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  1.8 := 5 PARA
  DATA
 ."                WEBER'S LAW PROGRAM " CR
 ."                ***** Order 0 ***** " CR
  1.3 0.4 1 32767 LXTRACT
  32767 STATS 5 CB := rms
 \                          15:42 12/05/97

 ." TEST FILE : " ifl current + . CR CR
 ." Do you judge the first or second to be perceptible ? "
   CR 1000 8 BEEP
." Enter 0 or 1 " #IN := resp \ 0 IS THE CORRECT RESPONSE
 resp 0 =
IF   county 1 + := county 0 := countn   \ IF CORRECT....
    1 := ok
    ELSE 0 := county countn 1 + := countn  0 := ok
 THEN ;

\ ORDER 1                               09:56 06.09.99
: ORDER1
  ifl current + 140 120 3 17 MERGE   \ STIMULUS
  200 201 200 3 18 MERGE     \ LIGHT
  1 DEL 32767 DEL
 ."  DATA DATA DATA " CR             \ RUN DATA
  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  1.8 := 5 PARA
  DATA
 ."                  WEBER'S LAW PROGRAM " CR
 ."                  ***** Order 1 ***** " CR
  0.1 0.4 1 32767 LXTRACT
  32767 STATS 5 CB := rms

\                             16:51 11/20/97
 ." TEST FILE : " ifl current + . CR CR
 ." Do you judge the first or second to be perceptible ? "
   CR 1000 8 BEEP
 ." Enter 0 or 1 " #IN := resp \ 1 IS THE CORRECT RESPONSE
  resp 1 =
  IF   county 1 + := county 0 := countn \ IF CORRECT....
      1 := ok
      ELSE 0 := county countn 1 + := countn 0 := ok
  THEN                      ;

\ NEXT STIMULUS                   17:58 22.12.98
: NEXTSTIM
  county correct = IF        \ CHANGE DIRECTION
            current 1- := current
            0 := county 0 := countn
            THEN            \
  countn ( correct = ) IF \ CHANGE DIRECTION
            current 1+ := current
            0 := county 0 := countn
          THEN          \
  current -15 MAX := current         \ STOP LOW NUMS
  current 18 MIN := current          \ STOP HIGH NUMS
         ;

\ STORE VALUES FOR PROGRAM STATUS           18:59 04.09.99
: STOREVAL
  rms        7774 STORE \ RMS VALUE
  county   FLOAT  7775 STORE \ NUMBER OF CORRECT +VE
  countn   FLOAT  7776 STORE \ NUMBER OF CORRECT -VE
  ok     FLOAT  7777 STORE \ LAST DIRECTION
  current  FLOAT  7778 STORE \ LAST STIMULUS
  resp     FLOAT  7779 STORE \ LAST RESPONSE
  ;
\                               13:01 15.01.99
: GO := ifl
  0  := current       \ SET current TO REFERENCE
  0  := county
  0  := countn
  3  := correct       \ SET NUMBER OF CORRECT RESPONSES REQU
  80 := repeats       \ SET NUMBER OF REPEATS
 88 DEL 0.5 := 12 PARA 0.5 := 13 PARA 88 RANDOM CLS \ SET UP RUN
 \ SET PARAMETERS TABLE
    1.0 := 1 PARA
    0.0 := 13 PARA
    0.0 := 12 PARA
    10.0 := 17 PARA
    200.0 := 18 PARA

\                                15:53 12/05/97
\        PARAMETERS
   2.0 := 7 PARA
  repeats 1 + 1 DO          \ SET UP LOOP
    CR 17 DEL               \
    CR 18 DEL               \
    I 88 VALUE FIX          \ RANDOM ORDER
     IF ORDER1  ELSE ORDER0  THEN
     STOREVAL
     NEXTSTIM               \
   LOOP                ;
```

Figure C6-2 Study 8: Masked thresholds, screenfiles to run an unmasked threshold test.

```
\                              14:09 05.02.01
\ SCREEN TO MA1 FILES
\ FOR STUDY 8
\
\      MASKER THRESHOLDS WITH FORCED-CHOICE
\
\              CREATED BY MIYUKI M
\
\
\ CREATE FILES                    09:58 06.09.99
  97 120 NDEL 0.0 := 13 PARA  0.6 := 11 PARA
: TAPER * TAPER* BRUN COPY END-MODULE ;

\ CREATE PAUSE
  140 DEL

\                              14:59 30.09.99
\ 125 Hz CENTRE NARROW BAND
  5000.0 := 10 PARA 0.1 := 12 PARA 0.0 := 13 PARA 97 RANDOM
  112.0 := 17 PARA 6.0 := 19 PARA 97 98 HIBUTTER
  141.0 := 18 PARA 6.0 := 19 PARA 98 99 LOBUTTER
  99 100 313 313 TAPER  0.0 := 12 PARA 140 SINE

\ 16 HZ CENTRE NARROW BAND
\ 5000.0 := 10 PARA 0.5 := 12 PARA 0.0 := 13 PARA 97 RANDOM
\ 14.1 := 17 PARA 6.0 := 19 PARA 97 98 HIBUTTER
\ 17.8 := 18 PARA 6.0 := 19 PARA 98 99 LOBUTTER
\ 99 100 313 313 TAPER 0.0 := 12 PARA  140 SINE

\ TAPER                           10:59 06.09.99
\ CREATE LIGHT
  200 201 NDEL
  2.5 := 12 PARA 0.6 := 11 PARA  250.0 := 14 PARA
  -2.5 := 13 PARA  200 SINE

\ CREATE OFF LIGHT
  0.0 := 12 PARA 0.6 := 11 PARA
  -2.5 := 13 PARA 201 SINE
```

```
\ CREATE OTHER FILES                     16:25 08.12.97
  1.2589 := constant 100 101 FILE*
  1.5849 := constant 100 102 FILE*
  1.9953 := constant 100 103 FILE*
  2.5119 := constant 100 104 FILE*
  3.1623 := constant 100 105 FILE*
  3.9811 := constant 100 106 FILE*
  5.0119 := constant 100 107 FILE*
  6.3096 := constant 100 108 FILE*
  7.9433 := constant 100 109 FILE*
  10.0000 := constant 100 110 FILE*
  12.5893 := constant 100 111 FILE*
  15.8489 := constant 100 112 FILE*

\                              16:25 08.12.97
  19.9526 := constant 100 113 FILE*
  25.1189 := constant 100 114 FILE*
  31.6228 := constant 100 115 FILE*
  39.8107 := constant 100 116 FILE*
  50.1187 := constant 100 117 FILE*
  63.0957 := constant 100 118 FILE*
  0.0000 := constant 100 120 FILE*
```

Figure C6-3 Study 8: Masked thresholds, screenfiles to set up masker stimuli

```
\                         14:10 05.02.01
\ MA2 BATCH JOBS
\ FOR STUDY 8
\
\     MASKER THRESHOLDS WITH FORCED-CHOICE
\
\         CREATED BY MIYUKI M
\
\ JOB TO PRESENT STIMULI             14:15 08.12.97
\ NEED FILES : 100  = REFERENCE
\ 101 = REF+1, 102 = REF+2, 103 = REF+3, 104 = REF+4, 105 REF+5
\ 106 = REF+6, 107 = REF+7, 108 = REF+8, 109 = REF+9, 110 REF+10
\ 111 = REF+11, 112 = REF+12, 113 = REF+13, 114 = REF+14,
\ 115 = REF+15, 116 = REF+16, 117 = REF+17, 118 = REF+18
\ 120 = NULL FILE, 140 = PAUSE, 200 = LIGHT, 201 = OFF LIGHT

: MODULE ;
: LXTRACT  " LXTRACT"  BRUN COPY  END-MODULE ;
 INTEGER resp INTEGER countn INTEGER dim 1 := dim
 INTEGER current INTEGER ifl INTEGER repeats INTEGER county
 INTEGER correct   INTEGER ok
 REAL rms   REAL value
 VARIABLE VOCVAR VARIABLE DPVAR
       value 1.0 := value
\ ORDER 0                     09:59 06.09.99
: ORDER0
  120 140 ifl current + 3 17 MERGE  \ STIMULUS
  200 201 200 3 18 MERGE       \ LIGHT
  1 DEL  32767 DEL
 ."  DATA DATA DATA " CR             \ RUN DATA

  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  1.8 := 5 PARA
  DATA
 ."                  WEBER'S LAW PROGRAM " CR
 ."                  ***** Order 0 ***** " CR
  1.3 0.4 1 32767 LXTRACT
  32767 STATS 5 CB := rms

 \                            15:42 12/05/97
 ." TEST FILE : " ifl current + . CR CR

." Do you judge the first or second to be perceptible ? "
  CR 1000 8 BEEP
." Enter 0 or 1 " #IN := resp \ 0 IS THE CORRECT RESPONSE
 resp 0 =
 IF   county 1 + := county 0 := countn   \ IF CORRECT....
    1 := ok
    ELSE 0 := county countn 1 + := countn  0 := ok  THEN ;

\ ORDER 1                          09:59 06.09.99
: ORDER1
  ifl current + 140 120 3 17 MERGE   \ STIMULUS
  200 201 200 3 18 MERGE    \ LIGHT
  1 DEL 32767 DEL
 ."  DATA DATA DATA " CR              \ RUN DATA
  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  1.8 := 5 PARA   DATA

 ."                  WEBER'S LAW PROGRAM " CR
 ."                  ***** Order 1 ***** " CR

  0.1 0.4 1 32767 LXTRACT
  32767 STATS 5 CB := rms
\                              16:51 11/20/97


 ." TEST FILE : " ifl current + . CR CR
 ." Do you judge the first or second to be perceptible ? "
   CR 1000 8 BEEP
 ." Enter 0 or 1 " #IN := resp \ 1 IS THE CORRECT RESPONSE
  resp 1 =
  IF   county 1 + := county 0 := countn \ IF CORRECT....
     1 := ok
     ELSE 0 := county countn 1 + := countn 0 := ok  THEN        ;

\ NEXT STIMULUS                         17:58 22.12.98
: NEXTSTIM
  county correct = IF            \ CHANGE DIRECTION
             current 1- := current
             0 := county 0 := countn
             THEN              \
  countn ( correct = ) IF \ CHANGE DIRECTION
          current 1+ := current
          0 := county 0 := countn
          THEN            \
 current -15 MAX := current            \ STOP LOW NUMS
 current 18 MIN := current             \ STOP HIGH NUMS
         ;
\ STORE VALUES FOR PROGRAM STATUS           16:02 03.09.99
: STOREVAL
 rms          8884 STORE \ RMS VALUE
 county   FLOAT  8885 STORE \ NUMBER OF CORRECT +VE
 countn   FLOAT  8886 STORE \ NUMBER OF CORRECT -VE
 ok      FLOAT  8887 STORE \ LAST DIRECTION
 current  FLOAT  8888 STORE \ LAST STIMULUS
 resp     FLOAT  8889 STORE \ LAST RESPONSE
 ;
\                            18:55 04.09.99
: GO := ifl
 0  := current       \ SET current TO REFERENCE
 0  := county
 0  := countn
 3  := correct        \ SET NUMBER OF CORRECT RESPONSES REQU
 80 := repeats        \ SET NUMBER OF REPEATS
88 DEL 0.5 := 12 PARA 0.5 := 13 PARA 88 RANDOM CLS \ SET UP RUN
\ SET PARAMETERS TABLE
   1.0 := 1 PARA
   0.0 := 13 PARA
   0.0 := 12 PARA
    8.0 := 17 PARA
   200.0 := 18 PARA


\                             15:53 12/05/97
\        PARAMETERS
   2.0 := 7 PARA
  repeats 1 + 1 DO          \ SET UP LOOP
   CR 17 DEL   CR 18 DEL            \
   I 88 VALUE FIX           \ RANDOM ORDER
   IF ORDER1  ELSE ORDER0  THEN
   STOREVAL
   NEXTSTIM              \
  LOOP               \
   ;
```

Figure C6-4 Study 8: Masked thresholds, screenfiles to run masker threshold test.

```
\                              14:09 05.02.01
\
\ SCREEN TO MASK FILES
\ FOR STUDY 8
\
\       MASKER LEVEL

\              CREATED BY MIYUKI M
\

\ 2.5 dB STEP                        11:42 04.10.99
  160 DEL

\ 1.0000 := constant 75 160 FILE*   \ 0 dB
\ 1.3335 := constant 75 160 FILE*   \ +2.5 dB
\ 1.7783 := constant 75 160 FILE*   \ +5.0 dB
\ 2.3714 := constant 75 160 FILE*   \ +7.5 dB
\ 3.1623 := constant 75 160 FILE*   \ +10.0 dB
\ 4.2170 := constant 75 160 FILE*   \ +12.5 dB
\ 5.6234 := constant 75 160 FILE*   \ +15.0 dB


\                               12:21 04.10.99
\ 7.4989 := constant 75 160 FILE*   \ +17.5 dB
\ 10.000 := constant 75 160 FILE*   \ +20.0 dB
\ 13.335 := constant 75 160 FILE*   \ +22.5 dB
\ 17.783 := constant 75 160 FILE*   \ +25.0 dB
\ 23.714 := constant 75 160 FILE*   \ +27.5 dB
\ 31.623 := constant 75 160 FILE*   \ +30.0 dB
\ 42.170 := constant 75 160 FILE*   \ +32.5 dB
\ 56.234 := constant 75 160 FILE*   \ +35.0 dB
\ 74.989 := constant 75 160 FILE*   \ +37.5 dB
\ 100.00 := constant 75 160 FILE*   \ +40.0 dB
\ 133.35 := constant 75 160 FILE*   \ +42.5 dB
\ 177.83 := constant 75 160 FILE*   \ +45.0 dB
\ 237.14 := constant 75 160 FILE*   \ +47.5 dB
\ 316.28 := constant 75 160 FILE*   \ +50.0 dB
```

```
\ 3 dB STEP                          12:55 04.10.99

\ 1.0000 := constant 75 160 FILE*   \ 0 dB
\ 1.4125 := constant 75 160 FILE*   \ + 3.0 dB
\ 1.9952 := constant 75 160 FILE*   \ + 6.0 dB
\ 2.8184 := constant 75 160 FILE*   \ + 9.0 dB
\ 3.9811 := constant 75 160 FILE*   \ +12.0 dB
\ 5.6234 := constant 75 160 FILE*   \ +15.0 dB
\ 7.9433 := constant 75 160 FILE*   \ +18.0 dB
\ 11.220 := constant 75 160 FILE*   \ +21.0 dB
\ 15.848 := constant 75 160 FILE*   \ +24.0 dB
\ 22.387 := constant 75 160 FILE*   \ +27.0 dB
  31.623 := constant 75 160 FILE*   \ +30.0 dB
```

Figure C6-5 Study 8: Masked thresholds. Screenfiles to set up masker levels.

```
\                             14:15 05.02.01
\ SCREEN TO MM1 FILES
\ FOR STUDY 8
\
\       MASKED THRESHOLDS SET UP
\
\               CREATED BY MIYUKI M
\
\
\
\ NEED FILES                          13:41 13.09.99
  72 123 NDEL 140 DEL 160 DEL 200 202 NDEL
: TAPER " TAPER" BRUN COPY END-MODULE ;

\ CREATE FREQUENCY OF TEST STIMULI
\ 16.0 := 14 PARA  0.3 := 12 PARA
\ 31.5 := 14 PARA  0.1 := 12 PARA
\ 63.0 := 14 PARA  0.1 := 12 PARA
  125.0 := 14 PARA 0.02 := 12 PARA
\ 250.0 := 14 PARA 0.1 := 12 PARA
\ 500.0 := 14 PARA 0.1 := 12 PARA

\ CREATE TEST FILE                    10:00 06.09.99
  0.6 := 11 PARA 0.0 := 13 PARA
  5000.0 := 10 PARA 99 SINE
  99 100 313 313 TAPER

\ CREATE ON LIGHT
  0.0 := 12 PARA 0.6 := 11 PARA
  2.5 := 13 PARA 200 SINE

\ CREATE OFF LIGHT
  0.0 := 12 PARA 0.6 := 11 PARA
  -2.5 := 13 PARA 201 SINE
\ CREATE FLUSH LIGHT
  6.0 := 14 PARA 0.6 := 11 PARA
  -2.5 := 13 PARA 2.5 := 12 PARA 202 SINE

\ CREATE MASKER                       12:08 16.09.99
\ 5000.0 := 10 PARA 1.0 := 12 PARA
\ 0.0 := 13 PARA  3.0 := 11 PARA 72 RANDOM
```

```
\ 125 Hz NARROW BAND MASKER
\ 112.0 := 17 PARA 6.0 := 19 PARA 72 73 HIBUTTER \ P MASK
\ 141.0 := 18 PARA 6.0 := 19 PARA 73 74 LOBUTTER \ P MASK

\ 16 Hz NARROW BAND MASKER
\ 14.1 := 17 PARA 6.0 := 19 PARA 72 73 HIBUTTER  \ NP MASK
\ 17.8 := 18 PARA 6.0 := 19 PARA 73 74 LOBUTTER  \ NP MASK

 5000.0 := 10 PARA 0.05 := 12 PARA 16.0 := 14 PARA
 0.0 := 13 PARA 3.0 := 11 PARA 74 SINE
 74 75 313 313 TAPER

\ CREATE MASKER LEVEL                 10:45 20.09.99
\ 1.0 := constant 75 160 FILE*      \ 0 dB
\ 1.3335 := constant 75 160 FILE*   \ +2.5 dB
\ 1.7783 := constant 75 160 FILE*   \ +5.0 dB
\ 2.3714 := constant 75 160 FILE*   \ +7.5 dB
\ 3.1623 := constant 75 160 FILE*   \ +10.0 dB
\ 4.2170 := constant 75 160 FILE*   \ +12.5 dB
\ 5.6234 := constant 75 160 FILE*   \ +15.0 dB
\ 7.4989 := constant 75 160 FILE*   \ +17.5 dB
\ 10.000 := constant 75 160 FILE*   \ +20.0 dB
\ 13.335 := constant 75 160 FILE*   \ +22.5 dB
\ 17.783 := constant 75 160 FILE*   \ +25.0 dB
\ 23.714 := constant 75 160 FILE*   \ +27.5 dB
\ 31.623 := constant 75 160 FILE*   \ +30.0 dB
\ 56.234 := constant 75 160 FILE*   \ +35.0 dB
\ 100.000 := constant 75 160 FILE*  \ +40.0 dB

\ CREATE OTHER FILES                  17:50 04.09.99
   1.2589 := constant 100 101 FILE* \ +2
   1.5849 := constant 100 102 FILE* \ +4
   1.9953 := constant 100 103 FILE* \ +6
   2.5119 := constant 100 104 FILE* \ +8
   3.1623 := constant 100 105 FILE* \ +10
   3.9811 := constant 100 106 FILE* \ +12
   5.0119 := constant 100 107 FILE* \ +14
   6.3096 := constant 100 108 FILE* \ +16
   7.9433 := constant 100 109 FILE* \ +18
  10.0000 := constant 100 110 FILE* \ +20
```

```
 12.5893 := constant 100 111 FILE* \ +22
 15.8489 := constant 100 112 FILE* \ +24

\                             17:54 04.09.99

 19.9526 := constant 100 113 FILE* \ +26
 25.1189 := constant 100 114 FILE* \ +28
 31.6228 := constant 100 115 FILE* \ +30
 39.8107 := constant 100 116 FILE* \ +32
 50.1187 := constant 100 117 FILE* \ +34
 63.0957 := constant 100 118 FILE* \ +36
 79.4328 := constant 100 119 FILE* \ +38
100.0000 := constant 100 120 FILE* \ +40
125.8925 := constant 100 121 FILE* \ +42
158.4893 := constant 100 122 FILE* \ +44
199.5262 := constant 100 123 FILE* \ +46

\ PAUSE FILE
 0.0 := constant 100 140 FILE*
\                             16:14 23.11.98
```

Figure C6-6 Study 8: Masked thresholds, Screenfiles to set up parameters for masked thresholds.

```
\                               14:11 05.02.01
\ MM2  BATCH JOBS
\ FOR STUDY 8
\    MASKED THRESHOLDS
\          CREATED BY MIYUKI M

\ JOB TO PRESENT STIMULI                 11:11 08/02/99
\ NEED FILES : 100  = REFERENCE
\ 101 = REF+1, 102 = REF+2, 103 = REF+3, 104 = REF+4, 105 REF+5
\ 106 = REF+6, 107 = REF+7, 108 = REF+8, 109 = REF+9, 110 REF+10
\ 111 = REF+11, 112 = REF+12, 113 = REF+13, 114 = REF+14,
\ 115 = REF+15, 116 = REF+16, 117 = REF+17, 118 = REF+18
\ 140 = PAUSE, 160 = MASKER, 200 = LIGHT, 201 = OFF LIGHT

: MODULE ;
: LXTRACT  " LXTRACT"  BRUN COPY  END-MODULE ;
  INTEGER resp INTEGER countn INTEGER dim 1 := dim
  INTEGER current INTEGER ifl INTEGER repeats INTEGER county
  INTEGER correct INTEGER ok
  REAL rms1 REAL rms2 REAL value REAL mask
  VARIABLE VOCVAR VARIABLE DPVAR
        value 1.0 := value

\ ORDER 0                        16:02 08.09.99
: ORDER0
  1 DEL 32767 DEL 23232 DEL 24242 DEL 141 DEL 142 DEL
  ifl current + 140 140 140 140
  ifl current + 140 7 141 MERGE   \ TEST
  140 140 160 3 142 MERGE       \ MASKER
  141 142 17 FILE+FILE
  202 201 201 200 201 200 201 7 18 MERGE  \ LIGHT
 ."  DATA DATA DATA " CR            \ RUN DATA
  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  4.2 := 5 PARA DATA
  0.1 0.4 1 23232 LXTRACT  1.3 1.0 1 24242 LXTRACT
  3.1 0.4 1 32767 LXTRACT  32767 STATS 5 CB := rms1
  23232 STATS 5 CB := rms2 24242 STATS 5 CB := mask

\                               12:33 28.07.99
 ." *** ORDER 0 *** " CR
 ." TEST FILE : " ifl current + . CR CR
." Do you judge the first or second to be perceptible ? "
  CR 1000 8 BEEP
." Enter 0 or 1 " #IN := resp \ 0 IS THE CORRECT RESPONSE
 resp 0 =
 IF   county 1 + := county 0 := countn  \ IF CORRECT....
     1 := ok
     ELSE 0 := county countn 1 + := countn  0 := ok  THEN ;

\ ORDER 1                        16:02 08.09.99
: ORDER1
  1 DEL 32767 DEL 23232 DEL 24242 DEL 141 DEL 142 DEL
 ifl current + 140 140 ifl current +
  140 140 140 7 141 MERGE   \ TEST
  140 140 160 3 142 MERGE       \ MASKER
  141 142 17 FILE+FILE
  202 201 201 200 201 200 201 7 18 MERGE  \ LIGHT
 ."  DATA DATA DATA " CR            \ RUN DATA
  17 STATS 1 CB := 3 PARA 1 CB 5.0 F/ := 2 PARA
  4.2 := 5 PARA DATA
  0.1 0.4 1 23232 LXTRACT  1.9 0.4 1 32767 LXTRACT
  3.1 1.0 1 24242 LXTRACT  32767 STATS 5 CB := rms1
  23232 STATS 5 CB := rms2 24242 STATS 5 CB := mask

\                               12:27 28.07.99
." *** ORDER 1 *** " CR
." TEST FILE : " ifl current + . CR CR
 ." Do you judge the first or second to be perceptible ? "
   CR 1000 8 BEEP
 ." Enter 0 or 1 " #IN := resp \ 1 IS THE CORRECT RESPONSE
  resp 1 =
  IF   county 1 + := county 0 := countn \ IF CORRECT....
      1 := ok
      ELSE 0 := county countn 1 + := countn 0 := ok
  THEN                   ;
\ NEXT STIMULUS                     17:58 22.12.98
: NEXTSTIM
  county correct = IF          \ CHANGE DIRECTION
            current 1- := current
            0 := county 0 := countn
            THEN            \
  countn ( correct = ) IF \ CHANGE DIRECTION
            current 1+ := current
            0 := county 0 := countn
            THEN          \
  current -15 MAX := current           \ STOP LOW NUMS
  current 18 MIN := current          \ STOP HIGH NUMS
            ;

\ STORE VALUES FOR PROGRAM STATUS            11:40 08/02/99
: STOREVAL
  rms l        9995 STORE \ MASKER+TEST VALUE
  rms2         9996 STORE \ TEST VALUE
  mask          9997 STORE \ MASKER VALUE
  current   FLOAT  9998 STORE \ LAST STIMULUS
  ;
\                            14:36 02.08.99
: GO := ifl
  0  := current       \ SET current TO REFERENCE
  0  := county
  0  := countn
  3  := correct       \ SET NUMBER OF CORRECT RESPONSES REQU
  80 := repeats       \ SET NUMBER OF REPEATS
 88 DEL 0.5 := 12 PARA 0.5 := 13 PARA 88 RANDOM CLS \ SET UP RUN
 \ SET PARAMETERS TABLE
    1.0 := 1 PARA
    0.0 := 13 PARA
    0.0 := 12 PARA
    8.0 := 17 PARA
    400.0 := 18 PARA

\                            15:53 12/05/97

\        PARAMETERS
   2.0 := 7 PARA
 repeats 1 + 1 DO         \ SET UP LOOP
   CR 17 DEL            \
   CR 18 DEL            \
   I 88 VALUE FIX          \ RANDOM ORDER
    IF ORDER1  ELSE ORDER0  THEN
    STOREVAL
    NEXTSTIM              \
  LOOP        ;         \
```

Figure C6-7 Study 8, Masked thresholds, screenfiles to run a masked threshold test.

APPENDIX D

EXPERIMENTAL DATA FOR SUBJECTIVE RESPONSES AND MEASURED VIBRATION

Table D1 Study 1 (in Chapter 4): Vibrotactile perception thresholds (ms^{-2} r.m.s.) with three psychophysical methods at 16 to 125 Hz for twelve subjects.

Method A (Continuous, yes-no)				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.046	0.107	0.221	0.119
S2	0.063	0.131	0.093	0.031
S3	0.069	0.106	0.286	0.148
S4	0.025	0.052	0.072	0.245
S5	0.073	0.115	0.257	0.138
S6	0.042	0.057	0.191	0.139
S7	0.031	0.06	0.22	0.203
S8	0.095	0.091	0.119	0.121
S9	0.026	0.072	0.238	0.24
S10	0.081	0.227	0.256	0.431
S11	0.137	0.113	0.137	0.188
S12	0.067	0.144	0.404	0.616
Mean	**0.063**	**0.106**	**0.208**	**0.218**
SD	*0.032*	*0.048*	*0.093*	*0.159*
25 %	0.039	0.069	0.133	0.134
Median	**0.065**	**0.107**	**0.221**	**0.168**
75 %	0.075	0.119	0.256	0.241
Method B (Intermittent, yes-no)				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.035	0.135	0.213	0.129
S2	0.029	0.080	0.040	0.027
S3	0.100	0.106	0.177	0.060
S4	0.026	0.051	0.069	0.073
S5	0.082	0.082	0.296	0.101
S6	0.027	0.072	0.135	0.087
S7	0.030	0.113	0.243	0.227
S8	0.035	0.082	0.056	0.066
S9	0.032	0.101	0.153	0.094
S10	0.033	0.245	0.161	0.233
S11	0.045	0.126	0.183	0.137
S12	0.043	0.123	0.626	0.569
Mean	**0.043**	**0.110**	**0.196**	**0.150**
SD	*0.023*	*0.049*	*0.155*	*0.146*
25 %	0.030	0.081	0.118	0.071
Median	**0.034**	**0.104**	**0.169**	**0.098**
75 %	0.043	0.124	0.221	0.159
Method C (Intermittent, forced-choice)				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.026	0.068	0.150	0.090
S2	0.027	0.052	0.063	0.031
S3	0.019	0.074	0.114	0.032
S4	0.023	0.056	0.088	0.054
S5	0.030	0.087	0.179	0.073
S6	0.031	0.060	0.037	0.059
S7	0.033	0.109	0.193	0.087
S8	0.050	0.078	0.066	0.031
S9	0.030	0.111	0.123	0.171
S10	0.034	0.126	0.150	0.202
S11	0.041	0.055	0.081	0.089
S12	0.029	0.120	0.341	0.314
Mean	**0.031**	**0.083**	**0.132**	**0.103**
SD	*0.008*	*0.027*	*0.082*	*0.085*
25 %	0.026	0.059	0.077	0.049
Median	**0.030**	**0.076**	**0.118**	**0.080**
75 %	0.033	0.110	0.157	0.110

Table D2 Study 2(in Chapter 5): Absolute perception thresholds (ms^{-2} r.m.s.) with three conditions measured at 8 to 500 Hz for twelve subjects.

Condition A (Plate)							
Subjects	8 Hz	16 Hz	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz
S1	0.083	0.041	0.030	0.019	0.011	0.015	0.123
S2	0.058	0.096	0.053	0.023	0.019	0.020	0.083
S3	0.028	0.059	0.017	0.070	0.021	0.023	0.056
S4	0.100	0.049	0.026	0.027	0.023	0.038	0.297
S5	0.089	0.070	0.089	0.022	0.020	0.050	0.255
S6	0.077	0.099	0.048	0.071	0.021	0.028	0.155
S7	0.105	0.077	0.034	0.044	0.033	0.039	0.139
S8	0.096	0.077	0.040	0.025	0.017	0.027	0.496
S9	0.072	0.028	0.038	0.020	0.019	0.026	0.199
S10	0.085	0.048	0.033	0.018	0.018	0.033	0.098
S11	0.073	0.110	0.027	0.036	0.016	0.030	0.112
S12	0.056	0.083	0.032	0.010	0.014	0.032	0.062
Mean	**0.077**	**0.070**	**0.039**	**0.032**	**0.019**	**0.030**	**0.183**
SD	**0.022**	**0.025**	**0.018**	**0.020**	**0.005**	**0.009**	**0.126**
25 %	0.068	0.049	0.029	0.020	0.017	0.025	0.094
Median	**0.080**	**0.073**	**0.034**	**0.024**	**0.019**	**0.029**	**0.131**
75 %	0.091	0.087	0.042	0.038	0.021	0.034	0.213
Condition B (Handle)							
Subjects	8 Hz	16 Hz	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz
S1	0.044	0.049	0.056	0.015	0.012	0.016	0.063
S2	0.158	0.064	0.040	0.024	0.017	0.019	0.098
S3	0.146	0.082	0.052	0.031	0.029	0.033	0.076
S4	0.121	0.039	0.034	0.040	0.014	0.043	0.139
S5	0.106	0.079	0.041	0.022	0.014	0.027	0.261
S6	0.086	0.103	0.124	0.043	0.023	0.028	0.142
S7	0.069	0.082	0.053	0.017	0.028	0.023	0.039
S8	0.102	0.071	0.042	0.052	0.014	0.018	0.042
S9	0.072	0.028	0.038	0.020	0.019	0.026	0.199
S10	0.085	0.089	0.092	0.019	0.015	0.020	0.084
S11	0.082	0.086	0.079	0.016	0.014	0.024	0.055
S12	0.081	0.055	0.046	0.012	0.013	0.020	0.068
Mean	**0.096**	**0.069**	**0.058**	**0.026**	**0.018**	**0.025**	**0.106**
SD	**0.033**	**0.022**	**0.027**	**0.013**	**0.006**	**0.007**	**0.068**
25 %	0.079	0.053	0.041	0.017	0.014	0.020	0.061
Median	**0.085**	**0.075**	**0.049**	**0.021**	**0.015**	**0.024**	**0.080**
75 %	0.110	0.083	0.062	0.034	0.020	0.027	0.140
Condition C (Fingertip)							
Subjects	8 Hz	16 Hz	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz
S1	0.008	0.015	0.027	0.086	0.046	0.076	0.323
S2	0.012	0.016	0.057	0.056	0.023	0.092	0.308
S3	0.020	0.017	0.051	0.030	0.017	0.038	0.428
S4	0.014	0.026	0.049	0.064	0.096	0.062	1.037
S5	0.029	0.031	0.043	0.259	0.113	0.998	3.093
S6	0.013	0.033	0.103	0.048	0.076	0.133	1.986
S7	0.017	0.029	0.023	0.070	0.063	0.050	0.110
S8	0.021	0.023	0.053	0.015	0.049	0.150	2.300
S9	0.028	0.025	0.064	0.060	0.062	0.250	0.958
S10	0.014	0.019	0.049	0.043	0.022	0.027	0.687
S11	0.016	0.026	0.034	0.038	0.048	0.091	0.608
S12	0.015	0.022	0.024	0.031	0.024	0.065	0.502
Mean	**0.017**	**0.024**	**0.048**	**0.067**	**0.053**	**0.169**	**1.028**
SD	**0.006**	**0.006**	**0.022**	**0.064**	**0.031**	**0.268**	**0.934**
25 %	0.014	0.019	0.032	0.037	0.024	0.059	0.401
Median	**0.015**	**0.024**	**0.049**	**0.052**	**0.049**	**0.083**	**0.648**
75 %	0.020	0.027	0.054	0.065	0.066	0.137	1.274

Table D3-1 Study 3 (in Chapter 6): Vibrotactile perception thresholds (ms^{-2} r.m.s) at 16 31.5, 63 and 125 Hz for twelve subjects measured with the Conditions A, B, and C.

***Condition A* (fingertip, with surround using the Vibrometer)**				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.031	0.062	0.082	0.105
S2	0.019	0.057	0.083	0.054
S3	0.027	0.101	0.190	0.177
S4	0.026	0.095	0.230	0.168
S5	0.072	0.033	0.073	0.050
S6	0.021	0.065	0.132	0.038
S7	0.037	0.045	0.046	0.027
S8	0.034	0.075	0.146	0.033
S9	0.037	0.056	0.062	0.089
S10	0.030	0.089	0.060	0.043
S11	0.025	0.059	0.083	0.099
S12	0.104	0.112	0.186	0.115
Mean	**0.038**	**0.071**	**0.115**	**0.083**
SD	*0.025*	*0.024*	*0.061*	*0.051*
25 %	0.026	0.057	0.071	0.042
Median	**0.030**	**0.064**	**0.083**	**0.071**
75 %	0.037	0.090	0.156	0.107
***Condition B* (fingertip, no surround using the Vibrometer)**				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.282	0.488	0.166	0.073
S2	0.146	0.090	0.050	0.039
S3	0.091	0.278	0.354	0.168
S4	0.241	0.183	0.265	0.095
S5	0.284	0.204	0.064	0.032
S6	0.071	0.199	0.064	0.026
S7	0.097	0.077	0.038	0.024
S8	0.085	0.166	0.113	0.034
S9	0.318	0.423	0.112	0.061
S10	0.181	0.258	0.055	0.033
S11	0.348	0.206	0.037	0.053
S12	0.333	0.258	0.073	0.036
Mean	**0.207**	**0.236**	**0.116**	**0.056**
SD	*0.106*	*0.120*	*0.099*	*0.041*
25 %	0.095	0.178	0.054	0.032
Median	**0.211**	**0.205**	**0.069**	**0.038**
75 %	0.293	0.263	0.127	0.064
***Condition C* (fingertip, no surround using the VP 30)**				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.088	0.271	0.124	0.063
S2	0.203	0.194	0.075	0.016
S3	0.109	0.345	0.329	0.062
S4	0.196	0.686	0.286	0.077
S5	0.119	0.187	0.098	0.039
S6	0.067	0.123	0.026	0.015
S7	0.201	0.284	0.076	0.020
S8	0.161	0.371	0.113	0.043
S9	0.217	0.194	0.179	0.076
S10	0.118	0.170	0.137	0.061
S11	0.230	0.161	0.046	0.044
S12	0.111	0.207	0.054	0.023
Mean	**0.152**	**0.266**	**0.128**	**0.045**
SD	*0.056*	*0.152*	*0.094*	*0.023*
25 %	0.111	0.183	0.070	0.022
Median	**0.140**	**0.200**	**0.105**	**0.043**
75 %	0.202	0.299	0.147	0.062

Table D3-2 Study 3 (in Chapter 6): Vibrotactile perception thresholds (ms^{-2} r.m.s) at 16 31.5, 63 and 125 Hz for twelve subjects measured with the Conditions D, E, and F.

Condition D (distal finger, 35 mm diameter, contact force=1 N)				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.160	0.152	0.095	0.033
S2	0.184	0.218	0.052	0.015
S3	0.143	0.383	0.184	0.059
S4	0.252	0.264	0.133	0.031
S5	0.080	0.211	0.125	0.035
S6	0.095	0.133	0.028	0.015
S7	0.115	0.113	0.053	0.012
S8	0.168	0.296	0.131	0.054
S9	0.152	0.283	0.196	0.075
S10	0.135	0.096	0.064	0.036
S11	0.264	0.207	0.045	0.026
S12	0.247	0.274	0.069	0.017
Mean	**0.166**	**0.219**	**0.098**	**0.034**
SD	*0.061*	*0.085*	*0.056*	*0.020*
25 %	0.130	0.148	0.053	0.017
Median	**0.156**	**0.215**	**0.082**	**0.032**
75 %	0.200	0.276	0.132	0.041
Condition E (distal finger, 35 mm diameter, contact force=5 N)				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.228	0.455	0.294	0.067
S2	0.154	0.169	0.069	0.020
S3	0.230	0.381	0.227	0.089
S4	0.190	0.275	0.157	0.060
S5	0.256	0.249	0.174	0.053
S6	0.107	0.184	0.054	0.037
S7	0.227	0.365	0.076	0.029
S8	0.082	0.355	0.080	0.041
S9	0.116	0.149	0.134	0.059
S10	0.195	0.179	0.180	0.053
S11	0.144	0.110	0.123	0.072
S12	0.163	0.205	0.068	0.020
Mean	**0.174**	**0.256**	**0.136**	**0.050**
SD	*0.056*	*0.109*	*0.074*	*0.021*
25 %	0.137	0.176	0.074	0.035
Median	**0.177**	**0.227**	**0.128**	**0.053**
75 %	0.227	0.357	0.175	0.061
Condition F (whole finger, contact force=5N)				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.052	0.079	0.049	0.031
S2	0.081	0.079	0.081	0.021
S3	0.136	0.229	0.326	0.079
S4	0.091	0.196	0.176	0.038
S5	0.041	0.049	0.091	0.029
S6	0.044	0.042	0.073	0.026
S7	0.065	0.063	0.075	0.030
S8	0.143	0.082	0.134	0.046
S9	0.075	0.061	0.042	0.017
S10	0.076	0.062	0.114	0.018
S11	0.069	0.075	0.121	0.054
S12	0.076	0.055	0.068	0.015
Mean	**0.079**	**0.089**	**0.112**	**0.034**
SD	*0.032*	*0.059*	*0.077*	*0.019*
25 %	0.062	0.059	0.071	0.021
Median	**0.075**	**0.069**	**0.086**	**0.030**
75 %	0.083	0.080	0.124	0.040

Table D3-3 Study 3 (in Chapter 6): Vibrotactile perception thresholds (ms^{-2} r.m.s) at 16 31.5, 63 and 125 Hz for twelve subjects measured with the Conditions Gand H.

Condition G (four fingers, contact force=5 N)				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.071	0.066	0.048	0.016
S2	0.046	0.071	0.044	0.013
S3	0.091	0.167	0.087	0.046
S4	0.059	0.164	0.046	0.014
S5	0.056	0.151	0.052	0.017
S6	0.041	0.042	0.061	0.016
S7	0.041	0.026	0.032	0.010
S8	0.058	0.201	0.122	0.035
S9	0.056	0.040	0.021	0.015
S10	0.068	0.085	0.068	0.015
S11	0.086	0.066	0.030	0.023
S12	0.046	0.040	0.024	0.012
Mean	**0.060**	**0.093**	**0.053**	**0.019**
SD	*0.016*	*0.060*	*0.029*	*0.011*
25 %	0.046	0.041	0.031	0.014
Median	**0.057**	**0.068**	**0.047**	**0.016**
75 %	0.069	0.154	0.063	0.019
Condition H (whole hand, contact force=5 N)				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.055	0.034	0.046	0.020
S2	0.046	0.045	0.029	0.016
S3	0.036	0.116	0.084	0.056
S4	0.049	0.038	0.039	0.017
S5	0.044	0.040	0.032	0.018
S6	0.050	0.029	0.027	0.015
S7	0.036	0.016	0.013	0.014
S8	0.081	0.050	0.047	0.037
S9	0.035	0.019	0.026	0.014
S10	0.085	0.056	0.026	0.017
S11	0.065	0.068	0.033	0.025
S12	0.061	0.036	0.022	0.018
Mean	**0.053**	**0.046**	**0.035**	**0.022**
SD	*0.017*	*0.027*	*0.018*	*0.012*
25 %	0.042	0.033	0.026	0.016
Median	**0.049**	**0.039**	**0.030**	**0.017**
75 %	0.062	0.051	0.041	0.021

Table D4-1 Study 4 (in Chapter 7): Vibrotactile perception thresholds (ms^{-2} r.m.s) at 16 31.5, 63 and 125 Hz for twelve subjects measured with the Test points 1, 2, and 3.

TEST POINT 1				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.098	0.079	0.190	0.125
S2	0.051	0.117	0.112	0.090
S3	0.036	0.122	0.188	0.140
S4	0.036	0.147	0.176	0.113
S5	0.034	0.111	0.265	0.411
S6	0.067	0.164	0.173	0.194
S7	0.048	0.071	0.047	0.060
S8	0.048	0.132	0.141	0.153
S9	0.068	0.088	0.166	0.136
S10	0.091	0.180	0.537	0.441
S11	0.059	0.224	0.401	0.621
S12	0.088	0.234	1.069	0.424
Mean	**0.060**	**0.139**	**0.289**	**0.242**
SD	*0.022*	*0.053*	*0.279*	*0.182*
25 %	0.045	0.105	0.160	0.122
Median	**0.055**	**0.127**	**0.182**	**0.147**
75 %	0.073	0.168	0.299	0.414
TEST POINT 2				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.029	0.065	0.132	0.058
S2	0.048	0.143	0.11	0.21
S3	0.066	0.124	0.214	0.222
S4	0.033	0.173	0.254	0.215
S5	0.122	0.143	0.465	0.33
S6	0.069	0.079	0.395	0.313
S7	0.033	0.039	0.045	0.039
S8	0.046	0.171	0.253	0.48
S9	0.064	0.091	0.116	0.154
S10	0.119	0.256	0.419	0.332
S11	0.047	0.146	0.503	0.489
S12	0.105	0.304	0.661	0.159
Mean	**0.065**	**0.145**	**0.297**	**0.250**
SD	*0.033*	*0.077*	*0.190*	*0.144*
25 %	0.043	0.088	0.128	0.158
Median	**0.056**	**0.143**	**0.254**	**0.219**
75 %	0.078	0.172	0.431	0.331
TEST POINT 3				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.037	0.109	0.252	0.147
S2	0.058	0.085	0.08	0.208
S3	0.069	0.124	0.21	0.228
S4	0.032	0.137	0.3	0.249
S5	0.077	0.116	0.479	0.961
S6	0.062	0.124	0.488	0.364
S7	0.045	0.051	0.05	0.06
S8	0.083	0.132	0.222	0.137
S9	0.064	0.08	0.093	0.177
S10	0.133	0.197	0.274	0.268
S11	0.056	0.093	0.336	0.457
S12	0.062	0.198	0.801	0.192
Mean	**0.065**	**0.121**	**0.299**	**0.287**
SD	*0.026*	*0.044*	*0.211*	*0.237*
25 %	0.053	0.091	0.181	0.170
Median	**0.062**	**0.120**	**0.263**	**0.218**
75 %	0.071	0.133	0.372	0.292

Table D4-2 Study 4 (in Chapter 7): Vibrotactile perception thresholds (ms^{-2} r.m.s) at 16 31.5, 63 and 125 Hz for twelve subjects measured with the Test points 4, 5, and 6.

TEST POINT 4				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.098	0.069	0.13	0.084
S2	0.044	0.161	0.203	0.091
S3	0.17	0.168	0.125	0.177
S4	0.073	0.152	0.255	0.133
S5	0.138	0.351	0.902	0.94
S6	0.075	0.219	0.257	0.13
S7	0.105	0.071	0.074	0.082
S8	0.064	0.179	0.374	0.302
S9	0.161	0.128	0.135	0.117
S10	0.455	0.695	0.609	0.212
S11	0.132	0.278	0.414	0.156
S12	0.182	0.243	0.393	0.151
Mean	**0.141**	**0.226**	**0.323**	**0.215**
SD	*0.108*	*0.168*	*0.239*	*0.237*
25 %	0.075	0.146	0.134	0.111
Median	**0.119**	**0.174**	**0.256**	**0.142**
75 %	0.163	0.252	0.398	0.186
TEST POINT 5				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.1	0.207	0.174	0.077
S2	0.036	0.123	0.226	0.086
S3	0.221	0.271	0.277	0.277
S4	0.067	0.184	0.319	0.083
S5	0.164	0.214	1.212	0.602
S6	0.102	0.234	0.341	0.131
S7	0.079	0.039	0.047	0.033
S8	0.081	0.33	0.37	0.718
S9	0.159	0.125	0.18	0.162
S10	0.618	0.635	0.527	0.295
S11	0.121	0.689	0.896	0.128
S12	0.238	0.45	0.383	0.129
Mean	**0.166**	**0.292**	**0.413**	**0.227**
SD	*0.155*	*0.202*	*0.330*	*0.218*
25 %	0.081	0.169	0.215	0.085
Median	**0.112**	**0.224**	**0.330**	**0.130**
75 %	0.178	0.360	0.419	0.282
TEST POINT 6				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.108	0.14	0.253	0.084
S2	0.086	0.162	0.114	0.129
S3	0.139	0.314	0.365	0.274
S4	0.064	0.194	0.282	0.111
S5	0.291	0.355	1.623	0.609
S6	0.114	0.305	0.218	0.165
S7	0.043	0.069	0.09	0.047
S8	0.072	0.213	0.576	0.456
S9	0.114	0.132	0.174	0.155
S10	0.237	0.516	0.416	0.172
S11	0.032	0.124	0.269	0.231
S12	0.151	0.629	1.175	0.269
Mean	**0.121**	**0.263**	**0.463**	**0.225**
SD	*0.077*	*0.170*	*0.467*	*0.162*
25 %	0.070	0.138	0.207	0.125
Median	**0.111**	**0.204**	**0.276**	**0.169**
75 %	0.142	0.324	0.456	0.270

Table D4-3 Study 4 (in Chapter 7): Vibrotactile perception thresholds (ms^{-2} r.m.s) at 16 31.5, 63 and 125 Hz for twelve subjects measured with the Test points 7 and 8.

TEST POINT 7				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.069	0.155	0.31	0.13
S2	0.075	0.098	0.412	0.329
S3	0.184	0.329	0.27	0.253
S4	0.069	0.097	0.23	0.207
S5	0.133	0.223	0.827	0.89
S6	0.059	0.15	0.171	0.253
S7	0.133	0.027	0.093	0.09
S8	0.069	0.232	0.211	0.356
S9	0.088	0.192	0.269	0.147
S10	0.305	0.475	1.29	1.019
S11	0.178	0.278	0.424	0.524
S12	0.197	0.41	0.941	0.73
Mean	**0.130**	**0.222**	**0.454**	**0.411**
SD	*0.075*	*0.133*	*0.368*	*0.311*
25 %	0.069	0.137	0.225	0.192
Median	**0.111**	**0.208**	**0.290**	**0.291**
75 %	0.180	0.291	0.525	0.576
TEST POINT 8				
Subjects	16 Hz	31.5 Hz	63 Hz	125 Hz
S1	0.086	0.138	0.339	0.178
S2	0.054	0.13	0.223	0.214
S3	0.143	0.425	0.32	0.253
S4	0.04	0.091	0.088	0.116
S5	0.113	0.317	1.306	1.915
S6	0.078	0.12	0.417	0.141
S7	0.051	0.068	0.075	0.081
S8	0.056	0.196	0.388	0.519
S9	0.067	0.088	0.159	0.119
S10	0.283	0.337	0.619	0.455
S11	0.062	0.214	0.598	0.783
S12	0.095	1.131	1.211	0.352
Mean	**0.094**	**0.271**	**0.479**	**0.427**
SD	*0.066*	*0.293*	*0.404*	*0.512*
25 %	0.056	0.113	0.207	0.136
Median	**0.073**	**0.167**	**0.364**	**0.234**
75 %	0.100	0.322	0.603	0.471

Table D5-1 Study 5: Measured vibration accelerations (ms^{-2} r.m.s.) presented to twenty subjects, for the test magnitude of 2 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	1.94	1.88	1.76	2.03	1.76	1.95	1.89	1.79	2.06	1.70	1.96	1.88	1.76	2.40	1.66	1.94	1.86	1.65	2.47	2.71	2.43	2.06	2.15	2.06	2.06
S2	1.87	1.84	2.09	1.87	2.95	1.88	1.82	2.16	1.94	3.38	1.89	1.84	2.10	2.37	3.20	1.89	1.86	2.12	2.37	3.34	1.90	1.87	2.12	1.78	2.31
S3	1.99	1.94	1.83	2.01	1.64	1.99	1.95	1.86	2.13	1.75	1.99	1.93	1.78	2.35	1.95	2.01	1.94	1.84	2.05	2.12	2.01	1.95	1.93	1.92	1.69
S4	1.98	2.05	2.31	1.94	2.61	2.00	2.00	2.33	2.06	3.13	2.00	2.04	2.27	2.04	2.59	2.01	2.03	2.28	2.00	3.03	2.00	2.03	2.32	2.31	2.19
S5	1.89	1.92	2.11	1.92	2.00	1.87	1.92	2.15	2.01	2.36	1.90	1.93	2.13	1.93	2.33	1.90	2.01	2.25	2.25	2.48	2.02	2.05	2.26	1.86	2.28
S6	1.97	2.00	2.17	2.04	2.10	1.97	2.00	2.28	2.22	2.16	1.97	2.00	2.08	2.01	2.36	1.99	1.99	2.23	2.38	2.33	1.98	2.00	2.26	1.75	2.19
S7	1.96	1.99	2.22	1.93	2.13	1.95	2.02	2.25	2.00	2.21	1.95	1.99	2.18	2.34	2.51	1.96	1.96	2.24	2.21	2.38	1.97	1.99	2.24	1.75	2.17
S8	1.92	1.87	1.78	1.90	2.01	1.92	1.87	1.83	2.24	1.91	1.93	1.87	1.77	2.37	2.06	1.94	1.87	1.81	1.95	2.10	1.93	1.88	1.84	1.91	1.77
S9	1.89	1.95	1.86	1.82	1.87	1.89	1.97	1.89	1.94	2.08	1.90	1.94	1.84	2.30	2.17	1.91	1.94	1.90	2.06	2.17	1.91	1.97	1.90	1.83	1.56
S10	2.07	2.14	2.20	2.11	1.63	2.07	2.14	2.20	2.24	1.83	2.09	2.13	2.14	2.40	1.87	2.07	2.10	2.18	2.40	2.35	2.08	2.14	2.24	2.01	1.79
S11	1.97	2.00	2.08	1.97	2.09	1.96	1.99	2.14	2.02	2.54	1.97	2.00	2.05	2.31	2.48	1.97	2.11	2.12	2.00	2.06	1.99	1.99	2.09	1.89	1.65
S12	2.07	2.13	2.21	2.12	1.90	2.06	2.13	2.22	2.13	2.14	2.06	2.13	2.23	2.18	2.27	2.07	2.11	2.23	2.07	2.36	2.08	2.15	2.24	1.96	1.62
S13	2.05	2.04	2.01	2.05	2.09	2.05	2.01	2.07	2.09	2.50	2.05	2.03	2.00	2.36	2.46	2.06	2.02	1.90	2.55	2.66	2.06	2.05	2.01	1.94	1.69
S14	2.04	2.07	2.15	2.08	2.14	2.04	2.05	2.20	2.10	2.51	2.03	2.06	2.13	2.43	2.21	2.04	2.09	2.11	2.23	2.55	2.08	2.11	2.19	1.96	1.68
S15	1.97	1.97	2.04	2.07	2.00	2.06	2.07	2.16	2.07	2.29	2.06	2.06	2.13	2.26	1.92	2.07	2.07	2.18	2.10	2.06	2.08	2.05	2.20	1.99	1.70
S16	2.07	2.15	2.22	2.18	1.99	2.07	2.14	2.24	2.23	2.22	2.07	2.15	2.21	2.31	2.38	2.07	2.12	2.19	2.34	2.32	2.08	2.12	2.24	1.96	1.72
S17	2.11	2.13	2.19	2.35	1.96	2.08	2.14	2.21	2.32	1.83	2.09	2.14	2.17	2.33	1.89	2.10	2.14	2.19	2.29	2.32	2.07	2.12	2.23	1.92	1.84
S18	1.95	1.98	1.88	1.89	1.92	1.91	1.93	1.91	1.98	2.31	1.91	1.93	1.88	2.25	2.29	1.90	1.89	1.95	2.15	2.19	1.91	1.95	1.87	1.75	1.46
S19	1.89	1.97	1.92	2.07	1.43	1.89	1.94	2.08	2.11	1.86	1.90	1.97	1.94	2.18	1.84	1.90	1.95	1.87	2.71	1.94	1.90	1.95	1.88	1.71	1.44
S20	1.91	1.91	1.81	1.95	1.80	1.91	1.92	1.85	2.25	1.78	1.93	1.91	1.77	1.91	2.07	1.93	1.88	1.82	2.22	2.06	1.93	1.92	1.87	1.90	1.76
Mean	**1.98**	**2.00**	**2.04**	**2.02**	**2.00**	**1.98**	**2.00**	**2.09**	**2.11**	**2.22**	**1.98**	**2.00**	**2.03**	**2.25**	**2.23**	**1.99**	**2.00**	**2.05**	**2.24**	**2.38**	**2.02**	**2.02**	**2.10**	**1.91**	**1.83**
SD	*0.07*	*0.09*	*0.17*	*0.12*	*0.33*	*0.07*	*0.09*	*0.17*	*0.11*	*0.44*	*0.07*	*0.09*	*0.17*	*0.16*	*0.35*	*0.07*	*0.10*	*0.19*	*0.20*	*0.35*	*0.12*	*0.09*	*0.16*	*0.14*	*0.27*
SD/ mean	0.04	0.05	0.09	0.06	0.16	0.04	0.05	0.08	0.05	0.20	0.04	0.05	0.08	0.07	0.16	0.04	0.05	0.09	0.09	0.15	0.06	0.04	0.08	0.07	0.15

Table D5-2 Study 5: Measured vibration accelerations (ms^{-2} r.m.s.) presented to twenty subjects, for the test magnitude of 4 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	3.94	3.78	3.54	4.26	3.56	3.94	3.78	3.60	4.29	3.50	3.96	3.78	3.49	4.72	3.35	3.95	3.74	3.41	4.74	5.04	4.09	4.11	4.30	4.13	4.11
S2	3.81	3.72	4.22	3.86	5.06	3.81	3.72	4.35	4.24	6.09	3.84	3.73	4.18	4.63	5.95	3.81	3.62	4.13	4.87	6.17	3.84	3.76	4.28	3.60	4.71
S3	4.04	3.65	3.66	4.28	3.30	4.02	3.95	3.74	4.78	3.64	4.04	3.87	3.63	4.79	3.94	4.07	3.90	3.70	4.06	3.88	4.07	3.78	3.78	3.79	2.92
S4	4.05	4.14	4.63	4.31	4.40	4.04	4.09	4.66	4.75	5.18	4.05	4.11	4.56	4.59	4.42	4.05	4.08	4.66	4.40	5.75	4.03	4.09	4.63	3.58	4.57
S5	3.83	3.85	4.22	4.01	4.08	3.81	3.87	4.32	4.19	4.49	3.84	3.87	4.28	4.39	4.67	4.07	4.05	4.78	4.64	4.93	4.11	4.12	4.52	3.75	4.71
S6	3.98	4.04	4.40	4.44	4.04	3.97	4.04	4.54	4.62	4.04	3.98	4.03	4.36	4.83	4.03	4.00	4.01	4.48	4.58	4.01	3.99	4.04	4.52	3.54	4.04
S7	3.99	4.01	4.46	3.89	4.32	3.92	4.07	4.53	4.19	4.75	3.95	3.93	4.41	4.73	5.04	3.98	3.98	4.60	4.40	4.82	4.01	4.02	4.47	3.49	4.36
S8	3.90	3.76	3.58	3.97	3.91	3.89	3.79	3.64	4.48	3.62	3.91	3.86	3.58	4.34	3.85	3.93	3.74	3.63	4.02	4.19	3.91	3.80	3.72	3.93	3.16
S9	3.84	3.95	3.72	3.89	3.76	3.84	4.00	3.82	4.31	4.14	3.85	3.94	3.66	4.40	3.89	3.87	3.90	3.76	4.33	4.07	3.87	3.96	3.81	3.68	3.16
S10	4.21	4.33	4.40	4.56	3.53	4.21	4.33	4.41	5.05	3.61	4.21	4.31	4.36	5.04	3.57	4.18	4.28	4.58	4.99	4.72	4.21	4.32	4.43	4.10	3.61
S11	4.02	4.04	4.16	4.13	3.85	4.00	4.03	4.28	4.37	4.32	4.02	4.03	4.10	4.43	4.17	4.01	3.99	4.22	4.30	4.25	4.25	4.02	4.39	3.97	3.50
S12	4.19	4.32	4.43	4.51	3.48	4.19	4.30	4.45	4.47	3.64	4.19	4.30	4.45	4.95	3.95	4.19	4.31	4.45	4.38	4.54	4.18	4.31	4.48	3.90	3.27
S13	4.15	4.14	4.02	4.31	3.74	4.16	4.12	4.15	4.49	4.22	4.16	4.13	3.98	5.03	4.46	4.17	4.06	3.96	5.11	4.60	4.17	4.13	4.05	3.89	3.43
S14	4.14	4.18	4.31	4.39	3.45	4.14	4.16	4.44	4.51	4.30	4.14	4.19	4.28	4.89	4.07	4.15	4.19	4.19	4.63	4.90	4.19	4.25	4.37	3.92	3.36
S15	4.19	4.16	4.27	4.27	3.52	4.18	4.19	4.33	4.34	3.92	4.19	4.16	4.22	4.56	3.60	4.17	4.15	4.36	4.50	4.20	4.16	4.14	4.36	3.97	3.43
S16	4.21	4.34	4.45	4.62	3.72	4.20	4.33	4.48	4.66	3.94	4.19	4.31	4.44	4.79	4.40	4.18	4.26	4.35	4.96	4.45	4.19	4.30	4.47	3.96	3.45
S17	4.23	4.40	4.35	4.92	3.59	4.22	4.31	4.43	4.88	3.58	4.25	4.28	4.36	5.01	3.33	4.26	4.27	4.49	4.86	4.19	4.19	4.27	4.46	3.81	3.72
S18	3.90	3.96	3.74	4.16	3.39	3.85	3.93	3.84	4.23	4.20	3.87	3.90	3.74	4.60	3.83	3.84	3.90	3.90	4.27	3.94	3.85	3.91	3.74	3.52	2.93
S19	3.83	3.96	3.88	4.51	2.97	3.84	3.95	4.10	4.61	3.67	3.85	3.97	3.90	4.69	3.17	3.86	3.96	3.91	5.50	3.44	3.82	3.95	3.76	3.43	2.88
S20	3.89	3.84	3.63	3.88	3.58	3.89	3.85	3.67	4.24	3.57	3.92	3.84	3.56	4.78	3.99	3.92	3.79	3.75	4.58	3.85	3.91	3.86	3.78	3.74	2.60
Mean	**4.02**	**4.03**	**4.10**	**4.26**	**3.76**	**4.01**	**4.04**	**4.19**	**4.49**	**4.12**	**4.02**	**4.03**	**4.08**	**4.71**	**4.08**	**4.03**	**4.01**	**4.17**	**4.61**	**4.50**	**4.05**	**4.06**	**4.22**	**3.79**	**3.60**
SD	*0.15*	*0.22*	*0.35*	*0.29*	*0.46*	*0.15*	*0.19*	*0.34*	*0.25*	*0.64*	*0.14*	*0.19*	*0.35*	*0.22*	*0.64*	*0.13*	*0.20*	*0.39*	*0.37*	*0.65*	*0.14*	*0.18*	*0.33*	*0.21*	*0.63*
SD/ mean	0.04	0.05	0.08	0.07	0.12	0.04	0.05	0.08	0.06	0.16	0.04	0.05	0.09	0.05	0.16	0.03	0.05	0.09	0.08	0.15	0.04	0.04	0.08	0.05	0.18

Table D5-3 Study 5: Subjective responses for the location test with the test magnitude of 2 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	8	2	3	3	2	9	3	2	2	2	7	4	3	3	3	8	8	6	5	7	8	8	8	7	4
S2	7	1	6	7	5	9	9	2	7	7	9	9	7	3	3	9	9	3	3	3	8	7	9	7	7
S3	3	2	1	3	2	7	9	3	2	2	7	9	3	3	3	7	9	4	4	4	8	8	4	4	6
S4	2	1	1	1	6	9	3	5	2	2	9	3	7	3	3	4	7	6	6	4	8	6	7	7	6
S5	5	1	1	2	1	2	2	5	2	2	7	3	3	3	3	7	9	6	7	7	9	8	9	7	7
S6	2	4	3	3	2	8	3	6	3	3	9	4	3	4	3	8	9	3	4	6	5	5	5	5	6
S7	2	1	1	1	2	7	6	2	2	2	7	3	3	3	3	7	7	7	7	7	9	9	8	7	7
S8	2	1	3	2	1	4	3	2	2	2	7	7	3	3	3	9	5	7	7	7	9	3	7	5	3
S9	7	2	1	1	2	8	9	7	2	2	7	5	9	3	3	9	7	7	7	3	9	9	3	5	7
S10	2	6	2	1	7	9	2	7	6	2	6	6	5	3	3	9	8	8	9	7	8	7	6	5	5
S11	3	2	1	5	2	9	7	5	3	2	7	3	3	3	3	9	6	9	7	7	9	9	7	5	5
S12	1	1	1	2	2	3	2	2	4	5	3	3	4	6	2	7	6	6	5	5	3	6	8	3	5
S13	9	2	3	7	1	9	9	6	5	2	8	3	7	7	3	9	9	9	7	7	8	9	9	7	7
S14	7	1	2	1	1	7	7	3	2	3	7	3	3	3	3	7	9	6	6	7	7	3	9	3	5
S15	7	2	1	2	5	9	3	2	2	2	9	3	3	3	3	7	9	6	6	4	9	9	3	3	5
S16	7	1	8	1	1	7	5	5	6	2	8	8	4	3	3	8	7	7	7	7	9	8	7	7	5
S17	6	2	3	2	2	7	5	5	2	2	8	3	7	3	8	9	9	7	4	3	7	8	8	3	3
S18	3	2	5	7	3	5	7	5	9	9	8	4	3	3	3	9	9	7	5	4	7	4	7	4	3
S19	5	6	2	7	1	5	6	2	2	2	3	3	3	3	3	7	9	7	5	3	7	5	7	7	5
S20	1	1	1	2	2	7	7	2	2	2	7	3	3	7	3	7	9	7	4	7	9	8	4	4	7

Table D5-4 Study 5: Subjective responses for the location test with the test magnitude of 4 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	9	7	5	2	1	9	5	5	2	1	9	4	6	3	3	9	9	9	5	7	9	8	8	7	7
S2	9	2	3	6	2	9	9	7	5	2	9	9	3	3	3	8	8	8	7	3	9	9	9	7	7
S3	7	7	1	1	3	7	3	3	8	2	7	3	4	3	3	7	7	6	7	8	8	9	9	7	7
S4	2	1	2	1	6	7	9	3	2	2	9	7	7	3	3	9	7	6	6	3	8	7	8	6	5
S5	6	8	7	5	1	7	2	3	2	1	7	3	6	3	3	9	7	7	7	7	9	8	9	7	7
S6	5	6	5	3	6	7	3	3	3	3	9	7	3	3	7	7	7	7	4	7	6	6	9	5	6
S7	2	1	1	1	2	8	9	6	2	5	9	7	7	3	3	9	9	3	7	7	9	9	9	7	5
S8	3	2	5	5	2	9	3	3	2	2	9	7	3	3	3	7	9	7	7	3	9	7	5	5	5
S9	7	3	1	1	1	9	7	7	7	2	9	7	9	3	3	9	9	7	7	7	8	9	7	3	5
S10	6	1	8	5	6	7	6	5	6	7	9	6	8	7	3	7	3	7	7	3	9	7	4	6	3
S11	7	3	2	2	1	9	7	3	2	2	9	7	7	3	7	9	9	7	5	3	9	9	3	7	5
S12	7	2	1	2	2	7	6	6	3	3	7	3	6	6	3	7	8	5	4	3	7	9	8	4	3
S13	9	7	3	3	2	8	9	5	2	2	8	9	9	3	3	8	9	9	7	7	8	9	8	7	7
S14	9	7	3	2	2	9	7	5	2	2	9	4	3	4	3	7	9	7	5	5	7	9	7	6	5
S15	9	1	5	2	2	9	3	3	2	2	9	5	3	3	3	9	9	6	6	4	9	9	3	7	4
S16	9	1	7	1	1	8	2	2	2	1	3	3	8	1	3	9	7	6	7	7	9	7	8	5	5
S17	8	6	9	2	2	8	2	5	2	2	6	8	7	3	3	9	7	7	7	7	9	9	8	7	6
S18	3	7	2	3	7	9	7	2	6	5	9	7	5	3	3	7	7	7	7	5	9	9	3	7	5
S19	5	1	7	1	3	7	7	5	2	2	9	7	7	3	3	3	9	7	5	3	7	9	4	4	6
S20	7	7	5	7	2	7	9	7	2	2	7	8	9	7	3	9	7	7	7	7	9	8	9	7	7

Table D5-5 Study 5: Modified response for the location test for the test magnitude of 2 ms^{-2} r.m.s.

'1': subjects feel the vibration at the contact location applied.
'0': subjects feel the vibration at any location other than at the contact location.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	0	0	0	0	0	0	0	1	1	1	0	0	1	1	1	0	0	1	1	1	0	0	0	1	1
S2	0	1	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1	1	1	0	1	0	1	1
S3	0	0	1	0	0	0	0	0	1	1	0	0	1	1	1	1	0	1	1	1	0	0	1	1	1
S4	0	1	1	1	0	0	0	0	1	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1
S5	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	0	1	1	1	0	0	0	1	1
S6	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1	1	1	1	1	1	1	1
S7	0	1	1	1	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1
S8	0	1	0	0	1	0	0	1	1	1	0	0	1	1	1	0	1	1	1	1	0	1	1	1	1
S9	0	0	1	1	0	0	0	0	1	1	0	0	0	1	1	0	1	1	1	1	0	0	1	1	1
S10	0	0	0	1	0	0	1	0	0	1	0	0	0	1	1	0	0	0	0	1	0	1	1	1	1
S11	0	0	1	0	0	0	0	0	0	1	0	1	1	1	1	0	1	0	1	1	0	0	1	1	1
S12	1	1	1	0	0	0	1	1	0	0	1	1	0	0	1	1	1	1	1	1	1	1	0	1	1
S13	0	0	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	0	1	1
S14	0	1	0	1	1	0	0	0	1	0	0	1	1	1	1	1	0	1	1	1	1	1	0	1	1
S15	0	0	1	0	0	0	0	1	1	1	0	1	1	1	1	1	0	1	1	1	0	0	1	1	1
S16	0	1	0	1	1	0	0	0	0	1	0	0	0	1	1	0	1	1	1	1	0	0	1	1	1
S17	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	0	0	1	1	1	1	0	0	1	1
S18	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	1	1	1	1	1	1
S19	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
S20	1	1	1	0	0	0	0	1	1	1	0	1	1	0	1	1	0	1	1	1	0	0	1	1	1
Total 1	2	9	9	6	6	1	3	8	12	15	2	11	12	16	19	9	7	17	19	20	6	9	12	20	20
Total 0	18	11	11	14	14	19	17	12	8	5	18	9	8	4	1	11	13	3	1	0	14	11	8	0	0

Table D5-6 Study 5: Modified response for the location test for the test magnitude of 4 ms^{-2} r.m.s.

'1': subjects feel the vibration at the contact location applied.
'0': subjects feel the vibration at any location other than at the contact location.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	0	0	0	0	1	0	0	0	1	1	0	0	0	1	1	0	0	0	1	1	0	0	0	1	1
S2	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0	1	1	0	0	0	1	1
S3	0	0	1	1	0	0	0	0	0	1	0	1	0	1	1	1	1	1	1	0	0	0	0	1	1
S4	0	1	0	1	0	0	0	0	1	1	0	0	0	1	1	0	1	1	1	1	0	1	0	1	1
S5	0	0	0	0	1	0	1	0	1	1	0	1	0	1	1	0	1	1	1	1	0	0	0	1	1
S6	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1	1	1	1	1	0	1	1
S7	0	1	1	1	0	0	0	0	1	0	0	0	0	1	1	0	0	1	1	1	0	0	0	1	1
S8	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	1	0	1	1	1	0	1	1	1	1
S9	0	0	1	1	1	0	0	0	0	1	0	0	0	1	1	0	0	1	1	1	0	0	1	1	1
S10	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1	1	1	1
S11	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	0	1	1	1	0	0	1	1	1
S12	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	1	1	0	0	1	1
S13	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0	0	0	1	1	0	0	0	1	1
S14	0	0	0	0	0	0	0	0	1	1	0	0	1	0	1	1	0	1	1	1	1	0	1	1	1
S15	0	1	0	0	0	0	0	0	1	1	0	0	1	1	1	0	0	1	1	1	0	0	1	1	1
S16	0	1	0	1	1	0	1	1	1	1	1	1	0	1	1	0	1	1	1	1	0	1	0	1	1
S17	0	0	0	0	0	0	1	0	1	1	0	0	0	1	1	0	1	1	1	1	0	0	0	1	1
S18	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	1	1	1
S19	0	1	0	1	0	0	0	0	1	1	0	0	0	1	1	1	0	1	1	1	1	0	1	1	1
S20	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	1	1	1	1	0	0	0	1	1
Total 1	0	6	4	6	5	0	3	2	13	15	1	4	5	16	18	8	9	17	20	19	4	5	8	20	20
Total 0	20	14	16	14	15	20	17	18	7	5	19	16	15	4	2	12	11	3	0	1	16	15	12	0	0

Table D6-1 Study 6: 'Frequency comparison test', measured vibration accelerations (ms^{-2} r.m.s.) for reference stimulus presented to twenty subjects, at the stimulus intensity of about 2 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	1.76	1.76	1.76	1.79	1.79	1.84	1.83	1.84	1.86	1.84	1.81	1.82	1.77	1.81	1.83	1.73	1.69	1.73	1.67	1.73	2.15	2.15	2.15	2.15	2.15
S2	1.74	1.74	1.74	1.74	1.74	1.76	1.75	1.75	1.75	1.75	1.71	1.74	1.72	1.71	1.72	1.72	1.72	1.69	1.71	1.70	1.79	1.79	1.79	1.80	1.80
S3	1.83	1.83	1.83	1.84	1.84	1.85	1.85	1.85	1.85	1.85	1.84	1.84	1.84	1.84	1.84	1.89	1.87	1.87	1.88	1.88	1.97	1.97	1.98	1.98	1.98
S4	1.88	1.88	1.88	1.89	1.89	1.90	1.90	1.89	1.89	1.90	1.88	1.85	1.84	1.88	1.87	1.90	1.90	1.87	1.89	1.90	1.93	1.92	1.93	1.93	1.93
S5	1.88	1.88	1.88	1.89	1.88	1.89	1.89	1.89	1.89	1.89	1.86	1.84	1.85	1.86	1.84	1.95	1.95	1.94	1.96	1.94	1.85	1.85	1.85	1.85	1.85
S6	1.89	1.89	1.89	1.89	1.89	1.85	1.82	1.85	1.85	1.85	1.79	1.79	1.79	1.79	1.80	1.79	1.80	1.80	1.80	1.79	1.86	1.86	1.86	1.86	1.86
S7	1.85	1.84	1.85	1.84	1.84	1.90	1.91	2.14	1.90	1.92	1.78	1.78	1.77	1.78	1.79	1.94	1.92	1.93	1.96	1.95	1.86	1.85	1.86	1.86	1.85
S8	1.77	1.78	1.78	1.77	1.79	1.81	1.81	1.81	1.80	1.81	1.76	1.76	1.76	1.75	1.77	1.80	1.81	1.80	1.81	1.81	1.90	1.89	1.91	1.91	1.89
S9	1.80	1.81	1.81	1.80	1.81	1.85	1.85	1.85	1.87	1.85	1.83	1.81	1.81	1.81	1.82	1.87	1.88	1.85	1.88	1.88	1.85	1.85	1.85	1.85	1.85
S10	1.82	1.82	1.82	1.82	1.82	1.83	1.82	1.83	1.83	1.82	1.77	1.78	1.78	1.78	1.78	1.83	1.82	1.81	1.82	1.82	1.80	1.81	1.78	1.79	1.79
S11	1.77	1.77	1.77	1.77	1.77	1.81	1.80	1.80	1.78	1.80	1.75	1.75	1.75	1.75	1.75	1.78	1.78	1.79	1.79	1.79	1.80	1.80	1.80	1.80	1.80
S12	1.80	1.80	1.80	1.80	1.80	1.82	1.82	1.83	1.83	1.82	1.81	1.80	1.80	1.80	1.80	1.83	1.83	1.82	1.82	1.83	1.83	1.83	1.83	1.83	1.83
S13	1.78	1.78	1.78	1.78	1.78	1.79	1.78	1.79	1.79	1.79	1.77	1.77	1.77	1.76	1.77	1.82	1.81	1.78	1.80	1.77	1.84	1.84	1.85	1.85	1.85
S14	1.78	1.77	1.77	1.78	1.77	1.81	1.81	1.81	1.81	1.80	1.77	1.80	1.77	1.79	1.77	1.78	1.76	1.74	1.76	1.75	1.78	1.78	1.78	1.78	1.78
S15	1.74	1.74	1.74	1.74	1.74	1.75	1.75	1.75	1.75	1.75	1.74	1.74	1.74	1.74	1.74	1.79	1.80	1.80	1.79	1.80	1.76	1.79	1.79	1.79	1.79
S16	1.80	1.80	1.80	1.80	1.80	1.81	1.82	1.81	1.81	1.81	1.80	1.81	1.80	1.80	1.80	1.90	1.78	1.78	1.79	1.78	1.81	1.80	1.81	1.79	1.82
S17	1.82	1.82	1.82	1.82	1.82	1.83	1.83	1.84	1.83	1.83	1.82	1.81	1.88	1.82	1.82	1.87	1.90	1.82	1.87	1.82	1.84	1.83	1.83	1.83	1.84
S18	1.78	1.78	1.79	1.78	1.79	1.84	1.84	1.84	1.84	1.84	1.78	1.77	1.78	1.78	1.78	1.79	1.80	1.80	1.82	1.84	1.78	1.80	1.78	1.78	1.79
S19	1.80	1.80	1.81	1.80	1.80	1.86	1.86	1.86	1.86	1.86	1.79	1.79	1.79	1.80	1.80	1.81	1.82	1.82	1.84	1.86	1.80	1.81	1.80	1.80	1.81
S20	1.92	1.93	1.94	1.93	1.94	1.94	1.94	1.92	1.93	1.94	1.93	1.93	1.94	1.94	1.94	1.94	1.94	1.94	1.93	1.92	1.94	1.82	1.94	1.82	1.81
Max	1.92	1.93	1.94	1.93	1.94	1.94	1.94	2.14	1.93	1.94	1.93	1.93	1.94	1.94	1.94	1.95	1.95	1.94	1.96	1.95	2.15	2.15	2.15	2.15	2.15
Min	1.74	1.74	1.74	1.74	1.74	1.75	1.75	1.75	1.75	1.75	1.71	1.74	1.72	1.71	1.72	1.72	1.69	1.69	1.67	1.70	1.76	1.78	1.78	1.78	1.78
Mean	**1.81**	**1.81**	**1.81**	**1.81**	**1.81**	**1.84**	**1.83**	**1.85**	**1.84**	**1.84**	**1.80**	**1.80**	**1.80**	**1.80**	**1.80**	**1.84**	**1.83**	**1.82**	**1.83**	**1.83**	**1.86**	**1.85**	**1.86**	**1.85**	**1.85**
SD	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*	*0.08*	*0.05*	*0.05*	*0.05*	*0.04*	*0.05*	*0.05*	*0.05*	*0.07*	*0.07*	*0.07*	*0.07*	*0.07*	*0.09*	*0.08*	*0.09*	*0.09*	*0.09*
SD/ mean	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05

Table D6-2 Study 6: 'Frequency comparison test', measured vibration accelerations (ms^{-2} r.m.s.) for <u>reference stimulus</u> presented to twenty subjects, at the stimulus intensity of about 4 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	3.58	3.57	3.59	3.58	3.57	3.68	3.66	3.69	3.70	3.69	3.59	3.57	3.58	3.57	3.61	3.51	3.44	3.53	3.50	3.61	3.65	3.69	4.30	4.30	3.65
S2	3.49	3.49	3.50	3.50	3.79	3.53	3.51	3.53	3.54	3.51	3.44	3.41	3.41	3.38	3.40	3.42	3.47	3.47	3.44	3.44	3.62	3.62	3.64	3.60	3.63
S3	3.70	3.69	3.70	3.70	3.69	3.72	3.70	3.72	3.71	3.72	3.70	3.70	3.72	3.71	3.70	3.76	3.76	3.75	3.77	3.76	3.96	3.96	3.96	3.96	3.96
S4	3.78	3.78	3.78	3.78	3.78	3.81	3.79	3.81	3.79	3.79	3.75	3.73	3.78	3.73	3.72	3.80	3.86	3.79	3.83	3.83	3.89	3.91	3.91	3.88	3.90
S5	3.77	3.77	3.77	3.77	3.77	3.79	3.78	3.79	3.80	3.79	3.73	3.77	3.76	3.75	3.75	3.90	3.99	3.95	3.96	3.90	3.69	3.68	3.69	3.69	3.68
S6	3.79	3.79	3.79	3.60	3.79	3.68	3.67	3.69	4.40	3.70	3.56	3.65	3.67	4.49	3.63	3.60	3.61	3.61	4.46	3.62	3.71	3.72	3.72	3.61	3.71
S7	3.70	3.69	3.69	3.69	3.70	3.83	3.77	3.86	3.81	3.81	3.53	3.61	3.60	3.59	3.57	3.99	3.91	3.98	4.01	4.01	3.73	3.73	3.72	3.73	3.73
S8	3.58	3.58	3.58	3.58	3.57	3.63	3.62	3.64	3.62	3.62	3.55	3.57	3.56	3.57	3.57	3.65	3.64	3.65	3.67	3.64	3.88	3.94	3.89	3.88	3.87
S9	3.66	3.65	3.65	3.64	3.64	3.75	3.73	3.73	3.74	3.74	3.66	3.64	3.63	3.64	3.64	3.75	3.73	3.74	3.76	3.77	3.71	3.71	3.71	3.71	3.72
S10	3.65	3.64	3.65	3.64	3.65	3.67	3.65	3.67	3.66	3.65	3.59	3.63	3.62	3.61	3.62	3.69	3.69	3.72	3.74	3.73	3.59	3.63	3.61	3.60	3.63
S11	3.56	3.56	3.56	3.55	3.56	3.63	3.62	3.63	3.63	3.63	3.49	3.50	3.49	3.50	3.49	3.55	3.56	3.56	3.56	3.56	3.59	3.59	3.59	3.59	3.59
S12	3.61	3.60	3.61	3.60	3.61	3.69	3.67	3.68	3.68	3.64	3.61	3.60	3.61	3.61	3.61	3.65	3.66	3.64	3.65	3.65	3.67	3.68	3.68	3.67	3.67
S13	3.57	3.57	3.57	3.57	3.57	3.61	3.59	3.60	3.61	3.61	3.54	3.53	3.54	3.54	3.54	3.67	3.65	3.71	3.71	3.71	3.70	3.70	3.70	3.70	3.70
S14	3.56	3.56	3.56	3.56	3.56	3.67	3.68	3.66	3.67	3.69	3.56	3.54	3.56	3.56	3.56	3.53	3.51	3.54	3.55	3.52	3.58	3.58	3.58	3.58	3.58
S15	3.50	3.50	3.50	3.50	3.50	3.51	3.52	3.52	3.51	3.51	3.50	3.49	3.49	3.49	3.49	3.57	3.62	3.56	3.57	3.59	3.56	3.57	3.56	3.56	3.56
S16	3.62	3.61	3.62	3.61	3.62	3.63	3.62	3.62	3.62	3.62	3.62	3.65	3.62	3.63	3.53	3.67	3.55	3.63	3.60	3.49	3.63	3.63	3.63	3.59	3.63
S17	3.65	3.64	3.64	3.67	3.68	3.67	3.69	3.70	3.64	3.71	3.64	3.63	3.64	3.67	3.64	3.81	3.75	3.56	3.64	3.63	3.68	3.68	3.67	3.58	3.53
S18	3.58	3.57	3.57	3.59	3.58	3.83	3.82	3.84	3.83	3.84	3.57	3.57	3.56	3.57	3.56	3.65	3.72	3.81	3.82	3.64	3.60	3.61	3.59	3.55	3.58
S19	3.61	3.61	3.61	3.63	3.61	3.87	3.86	3.87	3.87	3.87	3.61	3.60	3.60	3.61	3.59	3.68	3.75	3.85	3.86	3.68	3.64	3.65	3.63	3.58	3.62
S20	3.79	3.78	3.78	3.86	3.45	3.82	3.78	3.50	4.01	3.80	3.83	3.79	3.56	4.13	3.17	3.84	3.77	3.46	4.71	3.45	3.85	3.73	3.59	4.42	3.52
Max	3.79	3.79	3.79	3.86	3.79	3.87	3.86	3.87	4.40	3.87	3.83	3.79	3.78	4.49	3.75	3.99	3.99	3.98	4.71	4.01	3.96	3.96	4.30	4.42	3.96
Min	3.49	3.49	3.50	3.50	3.45	3.51	3.51	3.50	3.51	3.51	3.44	3.41	3.41	3.38	3.17	3.42	3.44	3.46	3.44	3.44	3.56	3.57	3.56	3.55	3.52
Mean	**3.64**	**3.63**	**3.64**	**3.63**	**3.63**	**3.70**	**3.69**	**3.69**	**3.74**	**3.70**	**3.60**	**3.61**	**3.60**	**3.67**	**3.57**	**3.68**	**3.68**	**3.67**	**3.79**	**3.66**	**3.70**	**3.70**	**3.72**	**3.74**	**3.67**
SD	*0.09*	*0.09*	*0.09*	*0.09*	*0.10*	*0.10*	*0.09*	*0.11*	*0.19*	*0.10*	*0.09*	*0.09*	*0.09*	*0.24*	*0.13*	*0.14*	*0.14*	*0.15*	*0.31*	*0.15*	*0.11*	*0.11*	*0.18*	*0.24*	*0.12*
SD/ mean	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.03	0.03	0.03	0.02	0.07	0.04	0.04	0.04	0.04	0.08	0.04	0.03	0.03	0.05	0.07	0.03

Table D6-3 Study 6: 'Frequency comparison test', measured vibration accelerations (ms^{-2} r.m.s.) for <u>test stimulus</u> presented to twenty subjects, at the stimulus intensity of about 4 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	1.94	1.87	1.76	2.06	1.67	1.96	1.92	1.84	2.09	1.78	1.96	1.88	1.78	2.36	1.80	1.96	1.89	1.74	2.36	2.51	2.05	2.06	2.15	2.06	2.06
S2	1.86	1.82	1.74	1.82	1.92	1.86	1.82	1.75	1.81	1.94	1.85	1.80	1.72	2.13	2.28	1.85	1.78	1.69	1.99	2.50	1.84	1.80	1.80	1.86	1.21
S3	2.00	1.97	1.84	2.10	1.66	1.99	1.99	1.85	2.35	1.74	2.00	1.97	1.84	2.40	1.77	2.02	1.96	1.87	2.24	1.89	2.00	1.96	1.97	2.09	1.42
S4	1.95	1.97	1.88	1.93	1.95	1.96	1.98	1.89	1.98	2.11	1.97	1.96	1.84	2.12	1.86	1.97	1.96	1.87	2.01	2.22	1.95	1.95	1.93	1.85	1.74
S5	1.97	1.98	1.88	1.93	2.00	1.96	1.98	1.89	1.94	2.02	1.97	1.97	1.84	2.03	2.20	1.98	1.92	1.95	2.11	2.27	2.00	1.97	1.85	1.97	1.74
S6	1.95	1.94	1.89	1.83	1.57	1.94	1.95	1.85	2.10	1.58	1.94	1.93	1.78	2.20	1.41	1.94	1.92	1.80	2.13	1.36	1.95	1.91	1.86	1.77	1.57
S7	1.95	1.94	1.85	1.95	1.49	1.91	1.94	2.66	2.17	1.68	1.94	1.94	1.77	2.69	1.86	1.95	1.89	1.94	2.45	1.97	1.94	1.93	1.86	1.73	1.56
S8	1.94	1.90	1.78	1.94	1.70	1.95	1.92	1.81	2.01	1.68	1.95	1.90	1.75	2.27	1.81	1.95	1.89	1.80	2.04	2.04	1.92	1.88	1.91	2.28	1.32
S9	1.96	1.90	1.81	1.89	1.95	2.19	2.07	1.86	1.93	1.94	2.28	2.48	1.82	1.91	1.95	2.14	2.42	1.87	1.89	1.97	1.72	1.87	1.85	1.91	1.95
S10	1.93	1.92	1.82	1.98	1.70	1.92	1.92	1.83	2.14	1.66	1.94	1.88	1.77	2.19	1.83	1.92	1.85	1.82	2.37	2.25	1.90	1.90	1.79	1.93	1.62
S11	1.92	1.87	1.77	1.90	1.51	1.92	1.89	1.80	1.95	1.67	1.92	1.87	1.75	2.36	1.99	1.92	1.86	1.79	2.20	2.37	1.93	1.85	1.80	1.83	1.65
S12	1.91	1.88	1.80	1.96	1.87	1.91	1.91	1.83	1.95	1.96	1.91	1.90	1.81	2.29	2.14	1.91	1.87	1.83	2.02	2.26	1.91	1.88	1.83	1.81	1.56
S13	1.89	1.88	1.78	1.87	1.92	1.89	1.88	1.79	1.88	1.95	1.89	1.87	1.77	2.19	2.09	1.90	1.84	1.77	2.06	2.10	1.89	1.88	1.85	1.76	1.63
S14	1.92	1.86	1.78	1.81	1.91	1.90	1.85	1.80	1.87	2.15	1.89	1.84	1.77	2.23	2.16	1.91	1.83	1.75	2.12	2.41	1.90	1.86	1.78	1.79	1.44
S15	1.90	1.84	1.74	1.80	2.05	1.90	1.85	1.75	1.82	2.07	1.90	1.83	1.74	1.90	2.12	1.90	1.82	1.80	1.93	1.99	1.90	1.82	1.79	1.86	1.63
S16	1.80	1.80	1.80	1.80	1.80	1.81	1.82	1.81	1.81	1.81	1.80	1.81	1.80	1.80	1.80	1.90	1.78	1.78	1.79	1.78	1.81	1.80	1.81	1.79	1.82
S17	1.92	1.90	1.82	1.98	2.14	1.90	1.89	1.84	1.97	2.24	1.91	1.90	1.89	2.15	2.09	1.91	1.88	1.82	2.20	2.12	1.91	1.86	1.83	1.79	1.79
S18	1.94	1.88	1.79	1.83	1.90	1.93	1.86	1.85	1.93	2.10	1.93	1.87	1.78	2.13	2.21	1.92	1.82	1.84	2.15	2.29	1.95	1.87	1.79	1.80	1.58
S19	1.93	1.90	1.80	1.85	1.89	1.93	1.86	1.93	1.96	2.18	1.93	1.88	1.79	2.28	2.18	1.94	1.88	1.78	2.11	2.02	1.95	1.89	1.82	1.75	1.57
S20	1.92	1.92	1.94	2.11	1.25	1.94	1.93	1.84	2.55	1.45	1.93	1.92	1.80	2.07	1.58	1.94	1.90	1.76	1.91	1.68	1.94	1.89	1.81	2.21	1.83
Max	2.00	1.98	1.94	2.11	2.14	2.19	2.07	2.66	2.55	2.24	2.28	2.48	1.89	2.69	2.28	2.14	2.42	1.95	2.45	2.51	2.05	2.06	2.15	2.28	2.06
Min	1.80	1.80	1.74	1.80	1.25	1.81	1.82	1.75	1.81	1.45	1.80	1.80	1.72	1.80	1.41	1.85	1.78	1.69	1.79	1.36	1.72	1.80	1.78	1.73	1.21
Mean	**1.92**	**1.90**	**1.81**	**1.92**	**1.79**	**1.93**	**1.91**	**1.87**	**2.01**	**1.89**	**1.94**	**1.92**	**1.79**	**2.18**	**1.96**	**1.94**	**1.90**	**1.81**	**2.10**	**2.10**	**1.92**	**1.89**	**1.85**	**1.89**	**1.64**
SD	*0.04*	*0.05*	*0.05*	*0.09*	*0.22*	*0.07*	*0.06*	*0.19*	*0.18*	*0.22*	*0.09*	*0.14*	*0.04*	*0.20*	*0.23*	*0.06*	*0.13*	*0.06*	*0.17*	*0.29*	*0.07*	*0.06*	*0.09*	*0.16*	*0.20*
SD/ mean	0.02	0.03	0.03	0.05	0.12	0.04	0.03	0.10	0.09	0.12	0.05	0.07	0.02	0.09	0.12	0.03	0.07	0.04	0.08	0.14	0.04	0.03	0.05	0.08	0.12

Table D6-4 Study 6: 'Frequency comparison test', measured vibration accelerations (ms^{-2} r.m.s.) for test stimulus presented to twenty subjects, at the stimulus intensity of about 4 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	3.95	3.82	3.59	4.29	3.42	3.95	3.84	3.70	4.42	3.57	3.97	3.82	3.58	4.79	3.58	4.00	3.80	3.52	4.54	4.59	3.91	3.76	4.31	4.12	3.27
S2	3.78	3.66	3.50	3.70	3.89	3.76	3.69	3.54	3.91	4.15	3.77	3.62	3.40	4.43	4.19	3.78	3.60	3.46	4.48	4.62	3.71	3.61	3.64	3.71	3.50
S3	4.06	3.97	3.70	4.45	3.39	4.05	3.99	3.72	4.92	3.52	4.18	3.97	3.72	5.15	3.44	4.07	3.95	3.75	4.37	3.94	4.03	3.96	3.99	4.21	3.24
S4	3.99	3.99	3.78	4.29	3.58	4.00	3.99	3.81	4.40	3.92	3.99	3.95	3.79	4.52	3.52	3.98	3.92	3.79	4.75	4.26	3.95	3.92	3.91	3.72	3.36
S5	4.00	3.99	3.77	4.27	3.29	3.99	3.99	3.79	4.30	3.81	3.98	3.96	3.77	4.57	3.68	3.98	3.88	3.94	4.64	4.29	4.04	3.97	3.69	3.96	3.53
S6	3.93	3.91	3.79	3.79	3.15	3.91	3.91	3.69	3.67	3.16	3.92	3.86	3.65	3.67	2.91	3.91	3.86	3.61	3.61	3.83	3.94	3.85	3.72	3.72	3.14
S7	3.93	3.89	3.69	3.83	3.08	3.89	3.91	3.88	4.40	3.34	3.92	3.82	3.61	5.47	3.72	3.92	3.77	3.98	4.99	3.65	3.94	3.89	3.72	3.49	3.16
S8	3.94	3.82	3.58	4.05	3.44	3.94	3.85	3.62	4.38	3.48	3.94	3.80	3.57	4.51	3.70	3.94	3.80	3.66	4.22	3.78	3.87	3.79	3.87	4.43	3.61
S9	3.85	4.31	3.66	3.83	3.95	4.30	4.77	3.73	3.88	3.94	4.15	5.26	3.64	3.80	3.95	4.08	5.28	3.75	3.76	4.00	3.47	3.76	3.71	3.85	3.94
S10	3.92	3.86	3.65	4.30	3.51	3.90	3.85	3.68	4.46	3.32	3.90	3.81	3.63	4.38	3.55	3.88	3.74	3.72	4.50	4.17	3.87	3.81	3.60	3.85	3.16
S11	3.90	3.77	3.56	4.06	3.15	3.89	3.79	3.63	4.16	3.45	3.90	3.76	3.49	4.62	3.62	3.89	3.72	3.56	4.70	4.48	3.91	3.81	3.59	3.68	3.32
S12	3.87	3.80	3.60	4.07	3.32	3.87	3.83	3.69	4.09	3.53	3.87	3.83	3.61	4.66	3.86	3.87	3.78	3.65	4.26	4.39	3.85	3.78	3.68	3.60	3.13
S13	3.84	3.79	3.58	4.01	4.01	3.83	3.78	3.61	4.03	4.03	3.85	3.76	3.55	4.63	4.63	3.85	3.68	3.70	4.34	4.34	3.82	3.78	3.70	3.53	3.53
S14	3.87	3.74	3.56	3.81	3.67	3.85	3.75	3.67	3.93	4.17	3.85	3.75	3.55	4.61	3.95	3.86	3.66	3.53	4.86	4.58	3.85	3.75	3.58	3.58	2.87
S15	3.85	3.71	3.50	3.82	3.47	3.85	3.72	3.51	3.82	3.64	3.85	3.69	3.49	3.93	3.43	3.86	3.65	3.57	3.96	3.82	3.84	3.66	3.56	3.70	3.25
S16	3.62	3.61	3.62	3.61	3.62	3.63	3.62	3.62	3.62	3.62	3.62	3.65	3.62	3.63	3.53	3.67	3.55	3.63	3.60	3.49	3.63	3.63	3.63	3.59	3.63
S17	3.88	3.82	3.64	3.50	3.59	3.87	3.81	3.69	4.10	4.14	3.87	3.79	3.64	4.10	3.80	3.85	3.79	3.53	4.48	3.77	3.85	3.75	3.68	4.71	4.54
S18	3.92	3.81	3.59	3.88	3.78	3.91	3.78	3.69	4.06	4.10	3.90	3.78	3.56	4.36	4.08	3.89	3.64	3.88	4.68	4.63	3.92	3.75	3.61	3.61	3.17
S19	3.91	3.81	3.60	3.95	3.47	3.89	3.79	3.78	4.54	4.23	3.90	3.79	3.57	4.63	3.89	3.92	3.78	3.62	4.46	3.78	3.95	3.82	3.64	3.51	3.16
S20	3.87	3.86	3.86	3.93	3.48	3.90	3.85	3.58	4.10	3.88	3.91	3.87	3.63	4.21	3.23	3.92	3.84	3.53	4.81	3.52	3.92	3.81	3.67	4.51	3.59
Max	4.06	4.31	3.86	4.45	4.01	4.30	4.77	3.88	4.92	4.23	4.18	5.26	3.79	5.47	4.63	4.08	5.28	3.98	4.99	4.63	4.04	3.97	4.31	4.71	4.54
Min	3.62	3.61	3.50	3.50	3.08	3.63	3.62	3.51	3.62	3.16	3.62	3.62	3.40	3.63	2.91	3.67	3.55	3.46	3.60	3.49	3.47	3.61	3.56	3.49	2.87
Mean	**3.89**	**3.85**	**3.64**	**3.97**	**3.51**	**3.91**	**3.87**	**3.68**	**4.16**	**3.75**	**3.91**	**3.88**	**3.60**	**4.43**	**3.71**	**3.91**	**3.83**	**3.67**	**4.40**	**4.10**	**3.86**	**3.79**	**3.72**	**3.85**	**3.41**
SD	*0.09*	*0.15*	*0.10*	*0.25*	*0.26*	*0.13*	*0.23*	*0.09*	*0.32*	*0.33*	*0.12*	*0.34*	*0.09*	*0.46*	*0.37*	*0.09*	*0.36*	*0.14*	*0.40*	*0.38*	*0.13*	*0.09*	*0.18*	*0.36*	*0.36*
SD/ mean	0.02	0.04	0.03	0.06	0.07	0.03	0.06	0.02	0.08	0.09	0.03	0.09	0.03	0.10	0.10	0.02	0.09	0.04	0.09	0.09	0.03	0.02	0.05	0.09	0.11

Table D6-5 Study 6: 'Frequency comparison test', ratio of measured acceleration (ms^{-2} r.m.s.) between reference stimulus and test stimulus ($\frac{\text{Reference}}{\text{Test}}$) for twenty subjects, at the stimulus intensity being set about 2 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	0.91	0.94	1.00	0.87	1.07	0.94	0.95	1.00	0.89	1.03	0.92	0.97	0.99	0.77	1.02	0.88	0.90	1.00	0.71	0.69	1.05	1.05	1.00	1.04	1.04
S2	0.94	0.96	1.00	0.96	0.91	0.95	0.96	1.00	0.96	0.90	0.92	0.96	1.00	0.80	0.75	0.93	0.97	1.00	0.86	0.68	0.97	1.00	1.00	0.97	1.48
S3	0.91	0.93	1.00	0.87	1.10	0.93	0.93	1.00	0.79	1.07	0.92	0.93	1.00	0.77	1.04	0.94	0.95	1.00	0.84	1.00	0.99	1.01	1.00	0.95	1.39
S4	0.96	0.95	1.00	0.98	0.97	0.97	0.96	1.00	0.96	0.90	0.95	0.94	1.00	0.89	1.01	0.96	0.97	1.00	0.94	0.86	0.99	0.99	1.00	1.04	1.11
S5	0.96	0.95	1.00	0.98	0.94	0.96	0.96	1.00	0.97	0.93	0.94	0.93	1.01	0.92	0.84	0.99	1.01	0.99	0.92	0.86	0.92	0.94	1.00	0.94	1.06
S6	0.97	0.97	1.00	1.03	1.20	0.96	0.93	1.00	0.88	1.17	0.92	0.93	1.01	0.81	1.28	0.92	0.94	1.00	0.85	1.32	0.95	0.97	1.00	1.05	1.19
S7	0.95	0.95	1.00	0.94	1.24	1.00	0.98	0.80	0.87	1.14	0.92	0.92	1.00	0.66	0.96	1.00	1.02	1.00	0.80	0.99	0.96	0.96	1.00	1.07	1.19
S8	0.91	0.94	1.00	0.92	1.05	0.93	0.94	1.00	0.90	1.08	0.90	0.93	1.01	0.77	0.98	0.92	0.96	1.00	0.88	0.89	0.99	1.00	1.00	0.84	1.44
S9	0.92	0.95	1.00	0.95	0.93	0.85	0.89	1.00	0.97	0.95	0.80	0.73	1.00	0.95	0.94	0.88	0.78	0.99	1.00	0.96	1.07	0.99	1.00	0.97	0.95
S10	0.94	0.95	1.00	0.92	1.07	0.95	0.95	1.00	0.85	1.10	0.92	0.95	1.00	0.81	0.97	0.95	0.98	0.99	0.77	0.81	0.95	0.95	1.00	0.93	1.11
S11	0.92	0.94	1.00	0.93	1.17	0.94	0.95	1.00	0.91	1.07	0.91	0.93	1.00	0.74	0.88	0.93	0.95	1.00	0.82	0.76	0.93	0.97	1.00	0.98	1.09
S12	0.94	0.96	1.00	0.92	0.96	0.95	0.96	1.00	0.94	0.93	0.95	0.95	1.00	0.79	0.84	0.96	0.98	0.99	0.90	0.81	0.96	0.98	1.00	1.01	1.17
S13	0.94	0.95	1.00	0.95	0.93	0.95	0.95	1.00	0.95	0.92	0.93	0.94	1.00	0.81	0.85	0.96	0.98	1.00	0.87	0.84	0.98	0.98	1.00	1.05	1.13
S14	0.93	0.95	1.00	0.98	0.93	0.95	0.98	1.00	0.97	0.84	0.94	0.98	1.00	0.80	0.82	0.93	0.96	1.00	0.83	0.73	0.94	0.96	1.00	0.99	1.24
S15	0.92	0.95	1.00	0.97	0.85	0.92	0.95	1.00	0.96	0.85	0.92	0.95	1.00	0.91	0.82	0.94	0.98	1.00	0.93	0.91	0.93	0.98	1.00	0.96	1.10
S16	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
S17	0.95	0.96	1.00	0.92	0.85	0.96	0.97	1.00	0.93	0.81	0.95	0.95	1.00	0.84	0.87	0.98	1.01	1.00	0.85	0.86	0.96	0.99	1.00	1.03	1.03
S18	0.92	0.95	1.00	0.97	0.94	0.95	0.99	1.00	0.95	0.88	0.92	0.94	1.00	0.84	0.80	0.93	0.99	0.98	0.85	0.80	0.91	0.96	1.00	0.99	1.13
S19	0.93	0.95	1.01	0.97	0.95	0.96	1.00	0.96	0.95	0.85	0.93	0.95	1.00	0.79	0.83	0.93	0.97	1.02	0.87	0.92	0.92	0.96	0.99	1.03	1.15
S20	1.00	1.01	1.00	0.91	1.54	1.00	1.01	1.04	0.75	1.34	1.00	1.00	1.08	0.93	1.23	1.00	1.02	1.10	1.01	1.14	1.00	0.96	1.07	0.82	0.99
Mean	**0.94**	**0.95**	**1.00**	**0.95**	**1.03**	**0.95**	**0.96**	**0.99**	**0.92**	**0.99**	**0.93**	**0.94**	**1.00**	**0.83**	**0.93**	**0.95**	**0.97**	**1.00**	**0.87**	**0.89**	**0.97**	**0.98**	**1.00**	**0.98**	**1.15**
SD	*0.03*	*0.02*	*0.00*	*0.04*	*0.16*	*0.03*	*0.03*	*0.05*	*0.06*	*0.13*	*0.04*	*0.05*	*0.02*	*0.08*	*0.14*	*0.04*	*0.05*	*0.02*	*0.08*	*0.15*	*0.04*	*0.02*	*0.02*	*0.07*	*0.14*
SD/ mean	0.03	0.02	0.00	0.04	0.16	0.03	0.03	0.05	0.07	0.14	0.04	0.06	0.02	0.10	0.15	0.04	0.06	0.02	0.09	0.17	0.04	0.03	0.02	0.07	0.13

Table D6-6 Study 6: 'Frequency comparison test', ratio of measured acceleration (ms^{-2} r.m.s.) between reference stimulus and test stimulus ($\frac{\text{Reference}}{\text{Test}}$) for twenty subjects, at the stimulus intensity being set about 4 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	0.91	0.93	1.00	0.83	1.05	0.93	0.95	1.00	0.84	1.03	0.90	0.93	1.00	0.75	1.01	0.88	0.91	1.00	0.77	0.79	0.93	0.98	1.00	1.04	1.12
S2	0.92	0.95	1.00	0.94	0.97	0.94	0.95	1.00	0.91	0.85	0.91	0.94	1.00	0.76	0.81	0.91	0.96	1.00	0.77	0.75	0.98	1.00	1.00	0.97	1.04
S3	0.91	0.93	1.00	0.83	1.09	0.92	0.93	1.00	0.75	1.06	0.89	0.93	1.00	0.72	1.07	0.93	0.95	1.00	0.86	0.95	0.98	1.00	0.99	0.94	1.22
S4	0.95	0.95	1.00	0.88	1.06	0.95	0.95	1.00	0.86	0.97	0.94	0.94	1.00	0.83	1.06	0.96	0.98	1.00	0.81	0.90	0.99	1.00	1.00	1.04	1.16
S5	0.94	0.95	1.00	0.88	1.15	0.95	0.95	1.00	0.88	0.99	0.94	0.95	1.00	0.82	1.02	0.98	1.03	1.00	0.85	0.91	0.91	0.93	1.00	0.93	1.04
S6	0.96	0.97	1.00	0.95	1.20	0.94	0.94	1.00	1.20	1.17	0.91	0.95	1.01	1.22	1.25	0.92	0.94	1.00	1.24	0.95	0.94	0.97	1.00	0.97	1.18
S7	0.94	0.95	1.00	0.96	1.20	0.98	0.97	0.99	0.87	1.14	0.90	0.94	1.00	0.66	0.96	1.02	1.04	1.00	0.80	1.10	0.95	0.96	1.00	1.07	1.18
S8	0.91	0.94	1.00	0.88	1.04	0.92	0.94	1.00	0.83	1.04	0.90	0.94	1.00	0.79	0.96	0.92	0.96	1.00	0.87	0.96	1.00	1.04	1.01	0.88	1.07
S9	0.95	0.85	1.00	0.95	0.92	0.87	0.78	1.00	0.96	0.95	0.88	0.69	1.00	0.96	0.92	0.92	0.71	1.00	1.00	0.94	1.07	0.99	1.00	0.97	0.94
S10	0.93	0.94	1.00	0.85	1.04	0.94	0.95	1.00	0.82	1.10	0.92	0.95	1.00	0.82	1.02	0.95	0.99	1.00	0.83	0.90	0.93	0.95	1.00	0.94	1.15
S11	0.91	0.94	1.00	0.88	1.13	0.93	0.96	1.00	0.87	1.05	0.89	0.93	1.00	0.76	0.96	0.91	0.96	1.00	0.76	0.79	0.92	0.94	1.00	0.98	1.08
S12	0.93	0.95	1.00	0.89	1.09	0.95	0.96	1.00	0.90	1.03	0.93	0.94	1.00	0.77	0.94	0.94	0.97	1.00	0.86	0.83	0.95	0.97	1.00	1.02	1.17
S13	0.93	0.94	1.00	0.89	0.89	0.94	0.95	1.00	0.90	0.90	0.92	0.94	1.00	0.76	0.76	0.95	0.99	1.00	0.85	0.85	0.97	0.98	1.00	1.05	1.05
S14	0.92	0.95	1.00	0.93	0.97	0.95	0.98	1.00	0.93	0.88	0.92	0.94	1.00	0.77	0.90	0.91	0.96	1.00	0.73	0.77	0.93	0.96	1.00	1.00	1.25
S15	0.91	0.94	1.00	0.91	1.01	0.91	0.95	1.00	0.92	0.97	0.91	0.95	1.00	0.89	1.02	0.93	0.99	1.00	0.90	0.94	0.93	0.97	1.00	0.96	1.10
S16	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
S17	0.94	0.95	1.00	1.05	1.02	0.95	0.97	1.00	0.89	0.90	0.94	0.96	1.00	0.90	0.96	0.99	0.99	1.01	0.81	0.96	0.96	0.98	1.00	0.76	0.78
S18	0.91	0.94	0.99	0.93	0.95	0.98	1.01	1.04	0.94	0.93	0.92	0.94	1.00	0.82	0.87	0.94	1.02	0.98	0.82	0.79	0.92	0.96	1.00	0.98	1.13
S19	0.92	0.95	1.00	0.92	1.04	0.99	1.02	1.03	0.85	0.92	0.92	0.95	1.01	0.78	0.92	0.94	0.99	1.07	0.87	0.97	0.92	0.95	1.00	1.02	1.15
S20	0.98	0.98	0.98	0.98	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Mean	**0.93**	**0.94**	**1.00**	**0.92**	**1.04**	**0.95**	**0.95**	**1.00**	**0.91**	**0.99**	**0.92**	**0.94**	**1.00**	**0.84**	**0.97**	**0.94**	**0.97**	**1.00**	**0.87**	**0.90**	**0.96**	**0.98**	**1.00**	**0.97**	**1.09**
SD	*0.03*	*0.03*	*0.00*	*0.06*	*0.08*	*0.03*	*0.05*	*0.01*	*0.09*	*0.09*	*0.03*	*0.06*	*0.01*	*0.13*	*0.10*	*0.04*	*0.07*	*0.02*	*0.11*	*0.09*	*0.04*	*0.02*	*0.01*	*0.07*	*0.11*
SD/ mean	0.03	0.03	0.00	0.06	0.08	0.03	0.05	0.01	0.10	0.09	0.03	0.06	0.01	0.15	0.10	0.04	0.07	0.02	0.13	0.10	0.04	0.03	0.01	0.07	0.10

Table D6-7 Study 6: 'Frequency comparison test', subjective responses of sensation greatness compared with the reference stimulus at 31.5 Hz, exposed to the stimulus intensity being set at about 2 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	250	200	100	100	100	250	100	100	50	70	150	200	100	100	70	180	130	100	100	60	200	150	100	70	60
S2	350	204	100	250	200	200	200	100	175	250	200	175	100	100	200	75	175	100	125	175	50	100	100	150	200
S3	200	100	100	50	70	200	150	100	70	50	220	150	100	50	30	200	180	100	50	40	200	100	100	150	50
S4	200	160	95	80	80	200	130	90	95	80	150	210	98	80	85	170	200	105	85	95	130	200	80	70	90
S5	200	110	100	105	105	200	130	80	100	90	170	140	100	70	90	100	180	100	50	50	115	160	100	105	60
S6	300	150	110	100	110	250	130	80	40	40	180	120	80	35	30	160	130	90	34	75	300	400	120	80	50
S7	500	200	100	110	90	500	200	100	60	70	300	250	100	110	80	300	250	100	60	60	100	200	100	110	80
S8	300	100	100	120	150	150	200	100	70	30	250	150	100	70	50	250	200	100	50	50	200	200	100	70	50
S9	120	100	100	170	250	120	110	100	200	250	80	80	100	170	150	90	90	100	150	140	80	100	100	130	150
S10	70	200	100	90	150	50	50	100	100	125	50	125	100	90	125	75	90	100	80	25	30	65	100	90	70
S11	140	110	100	95	95	140	120	105	95	90	135	110	95	95	90	135	120	100	95	90	120	105	100	90	95
S12	300	210	95	70	85	220	175	100	98	85	250	180	100	90	95	210	160	100	90	80	200	150	100	60	90
S13	300	150	100	120	50	400	150	100	75	25	250	200	100	25	25	300	200	100	50	25	250	150	100	50	25
S14	200	150	95	70	80	200	175	100	60	120	225	175	100	80	70	200	175	100	80	70	150	175	105	80	75
S15	300	200	100	110	75	250	150	100	25	25	50	150	80	80	70	70	150	100	20	30	50	125	100	110	30
S16	200	100	100	100	100	250	123	100	100	75	200	200	100	75	75	100	100	100	50	50	200	100	75	50	50
S17	97	80	95	110	120	215	105	100	80	107	180	120	100	105	120	80	20	100	75	80	150	120	80	180	70
S18	223	160	90	110	95	160	130	101	88	102	160	110	100	105	120	65	115	140	85	90	120	110	107	90	150
S19	350	200	100	100	120	150	250	100	80	90	150	170	110	100	100	150	180	100	90	110	250	200	120	150	100
S20	90	150	95	98	110	200	120	100	110	90	200	115	100	95	90	120	120	100	120	90	120	150	100	80	90
Max	500	210	110	250	250	500	250	105	200	250	300	250	110	170	200	300	250	140	150	175	300	400	120	180	200
Min	70	80	90	50	50	50	50	80	25	25	50	80	80	25	25	65	20	90	20	25	30	65	75	50	25
Mean	235	152	99	108	112	215	145	98	89	93	178	157	98	86	88	152	148	102	77	74	151	153	99	98	82
Median	212	150	100	100	100	200	130	100	84	88	180	150	100	90	88	143	155	100	80	73	140	150	100	90	73

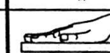
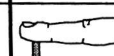
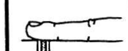
Table D6-8 Study 6: 'Frequency comparison test', subjective responses of sensation greatness compared with the reference stimulus at 31.5 Hz, exposed to the stimulus intensity being set at about 4 ms^{-2} r.m.s.

	Condition A					Condition B					Condition C					Condition D					Condition E				
	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125	8	16	31.5	63	125
S1	300	200	100	80	100	300	150	130	70	60	300	150	100	80	80	250	180	110	150	50	200	180	110	70	90
S2	250	300	100	250	250	300	300	125	125	225	250	250	100	150	225	75	200	100	150	150	75	250	100	175	300
S3	250	125	90	80	100	250	125	100	70	50	250	150	100	60	100	250	200	100	120	50	200	150	75	125	80
S4	220	190	95	85	85	220	190	105	95	80	180	190	115	75	75	110	210	93	85	85	220	240	110	80	93
S5	250	130	90	105	120	210	120	100	100	95	210	110	100	80	105	150	190	100	90	60	160	150	100	100	70
S6	200	140	80	110	80	250	140	120	50	70	175	120	110	80	80	203	126	97	36	36	180	200	90	120	40
S7	400	150	100	90	120	500	200	100	70	60	400	250	100	110	90	400	200	100	50	50	300	200	100	90	60
S8	300	150	100	70	50	300	200	70	50	150	200	150	120	60	30	300	250	100	70	30	200	150	90	150	50
S9	140	100	100	160	300	120	130	100	180	300	70	60	100	170	250	70	60	100	100	200	60	120	100	170	200
S10	50	125	100	150	160	80	75	100	120	110	60	80	100	90	140	25	60	100	85	75	20	80	100	95	50
S11	145	130	100	95	90	50	120	100	90	90	135	115	100	95	90	130	125	100	95	90	140	120	105	110	90
S12	400	200	100	95	90	200	180	100	80	80	300	190	100	90	95	250	200	105	90	90	250	170	100	80	50
S13	400	150	100	75	75	450	200	100	50	50	400	200	100	25	25	400	200	100	40	40	300	100	100	75	75
S14	275	175	100	75	65	250	220	90	70	60	250	180	105	75	80	250	250	100	50	80	180	200	110	65	60
S15	350	175	100	120	80	300	175	120	80	70	120	160	100	60	20	180	200	110	28	35	250	200	100	70	40
S16	300	200	100	100	100	300	200	120	103	79	300	100	100	200	75	200	200	100	50	50	150	100	101	75	25
S17	250	130	90	100	60	300	115	100	115	108	150	95	105	115	120	90	180	105	90	130	200	130	110	80	90
S18	300	160	106	85	89	200	170	180	90	115	108	150	100	75	88	160	150	100	80	68	160	190	85	110	132
S19	350	200	100	90	110	200	220	100	100	110	200	250	100	80	100	200	200	100	110	90	150	300	100	170	100
S20	110	180	100	120	90	250	150	100	95	120	250	150	100	95	90	250	160	100	80	90	180	170	100	90	90
Max	400	300	106	250	300	500	300	180	180	300	400	250	120	200	250	400	250	110	150	200	300	300	110	175	300
Min	50	100	80	70	50	50	75	70	50	50	60	60	100	25	20	25	60	93	28	30	20	80	75	65	25
Mean	262	166	98	107	111	252	169	108	90	104	215	155	103	93	98	197	177	101	82	77	179	170	99	105	89
Median	263	155	100	95	90	250	173	100	90	85	205	150	100	80	90	200	200	100	85	72	180	170	100	93	78

APPENDIX E

PSYCHOPHYSICAL MEASUREMENT CONDITIONS FROM OTHER STUDIES

Table E1. A comparison of psychophysical measurement conditions corresponding the absolute thresholds shown in Figure 2-13.

Year	Author(s)	Locations	Methodology	Vibration stimuli				Input conditions			Subjects		Environmental	
				Frequency range	Axis	Duration	Step rate	Position	Contactor status	Force status	Number (M/F)	Age	Skin temp.	Room temp.
1953	Sherrick	Fingertip (right, index finger)	Modification of *MOL	40-1200 Hz (10)	X	Δ	Δ		3.7 mm Ø no surround	Δ	4 (M)	Δ	Δ	Δ
1955	Ohno	Fingertip (right, index finger)	*MOL (descending)	50-1000 Hz (15)	X	Δ	Δ		0.7 cm² (contact area)	1 N push	10 (M)	22-59	Δ	Δ
1958	Obata	Four fingertips (excl. little finger)	Modification of *MOL (descending)	5-1000 Hz (19)	X	Δ	Δ		Table (duralumin)	1-3 N push	10 (M)	21-34	Δ	Δ
1962	Verrillo	Finger (second phalanx of third finger)	*MOL	25-640 Hz (7)	X	1 sec.	1 dB		6 mmØ surround with 1 mm gap	Δ	4	Δ	Δ	Δ
1967	Miwa	Whole hand	*MOPC	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	*MOA	25-1000 Hz (16)	X	Δ	–		Handle 1.905 cm Ø	8.896 N grip	8	Δ	Δ	Δ
1978	Gescheider *et al.*	Thenar eminence	*Békésy	25-700 Hz (10)	X	1 sec. 1-2 min/test	1 dB/sec.		2.5 mmØ surround with 1 mm gap	Δ	5	20-39	Δ	Δ
1984	Lundström	Fingertip	*Békésy	20-1000 Hz (13)	X	25-30 sec/test	10 dB/ sec.		9 mm Ø no surround	0.8N/cm²	6 (3M/3F)	30-39	± 4 °C	± 2 °C
1986	Hayward	Fingertip (index finger)	Up-down *MOL	16-500 Hz (16)	X	30-60 sec/test	Δ		6 mm Ø surround with 2 mm gap	2 N push	4 (3M/1F)	22-27	Δ	Δ
1986	Shimizu & Ooishi	Two fingertips (right, index finger & middle finger)	*MOC	10-800 Hz (14)	X, Z	Δ	Δ		Round table 50 mm Ø	adjusted by subjects	15	21-23	Δ	Δ
1988	Bolanowski *et al.*	Fingertip	*2AFC	0.4-500 Hz (25)	X	700 ms 3-6 min/test	1 dB		19.2 mmØ surround with 1 mm gap	–	5 (3M/2F)	20-49	30 °C	Δ
1996	Booth	Fingertip	*Békésy	16-500 Hz (16)	X	30 sec/test	5dB/sec.		6 mm Ø surround with 2 mm gap	2 N push	12 (M)	20-30	above 25 °C	34-37 °C

*MOL = Method of limits *MOA = Method of adjustment *MOC = Method of constant *MOPC = Method of paired matching *Békésy = von Békésy method
*2AFC = Two alternative forced choice tracking method X = vertical, Z = horizontal Δ = not specified or lack of report – = not necessary