UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS

Institute of Sound and Vibration Research

VIBRATION INTENSITY DIFFERENCE THRESHOLDS

by

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Thesis for the degree of Doctor of Philosophy

2009

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

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INSTITUTE OF SOUND AND VIBRATION RESEARCH

Doctor of Philosophy

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The intensity difference threshold is defined as 'the difference in the intensity of two stimuli which is just sufficient for their difference to be detected'.

The aim of this thesis is to advance understanding of the perception of vibration intensity differences in humans. In addition to increasing understanding of the tactile senses, knowledge of difference perception could inform various applications such as the optimisation of the vibration characteristics of vehicles and the design of human–machine interfaces involving communication via the sense of touch.

Absolute thresholds for the perception of vibration in the glabrous skin have been modelled by 'channels' within the somatosensory system that predict the effects of vibration frequency, vibration magnitude, vibration duration and contact conditions. Difference thresholds are less well understood and there is little knowledge of their dependence on vibration characteristics and contact conditions.

In this thesis, psychophysical methods were employed to determine the difference thresholds with various input conditions (whole-body vibration, foot-transmitted vibration, grasping a vibrating handle, and localised excitation of the hand and the forearm). Five experiments investigated the dependence of difference thresholds on vibration magnitude, vibration frequency, the responses of the somatosensory channels of the skin (especially the Pacinian and the non-Pacinian I channels) as well as the location of the vibration input, information from other sensory systems, and the presence of masking vibration.

The first experiment tested the hypothesis that relative difference thresholds (i.e. the percentage change in vibration magnitude required for the change to be detected) for vertical whole-body vibration depend on the frequency and magnitude of the vibration. Relative difference thresholds were found to be independent of vibration magnitude except at the lowest frequency (2.5 Hz) and the highest frequency (315 Hz), where the change in motion may have been perceived by vision and hearing, respectively. The second and third experiments investigated the dependence of difference thresholds on the frequency and magnitude of hand-transmitted vibration and foot-transmitted vibration. The experiments produced similar results, with difference thresholds independent of the frequency of vibration and only dependent on the magnitude of vibration at 125 Hz, where higher magnitudes (18 dB sensation level and above) produced greater relative difference thresholds. The fourth experiment tested the hypothesis that a low-magnitude low-frequency masking vibration (at 16 Hz) would not affect high-frequency difference thresholds (at 125 Hz). It was found that the low-frequency masker only increased difference thresholds when its magnitude was greater than 12 dB SL. The final experiment with localised vibration at the hand and arm tested the hypothesis that NPI and P channels have different relative difference thresholds. Overall, there was no significant difference between the relative difference thresholds of vibration mediated by the NPI channel (at 10 Hz) and the P-channel (at 125 Hz), but the relative difference thresholds of the P-channel tended to be lower than those of the NPI-channel, as in experiments II and III.

Depending on the test conditions, the median unmasked relative difference thresholds were in a range from 0.1 to 0.6. There was a tendency for the relative difference thresholds to decrease with increasing contact area, with whole-body vibration producing the smallest relative difference thresholds and localised vibration producing the greatest relative difference thresholds. From the results of all five experiments, it was concluded that excitation area and cues from other senses were more likely to cause relative difference thresholds to depend on the frequency and magnitude of vibration, than any differences in discrimination capability between the P and NPI channels. Other findings include a possible reduction in the discrimination capability of the P-channel with increasing magnitude of vibration (in Experiments II and III) and the suggestion of lower relative difference thresholds for the NPII channel (in Experiment V).

DECLARATION OF AUTHORSHIP

I, **Nazım Gizem Forta**

declare that the thesis entitled

Vibration Intensity Difference Thresholds

and the work presented in it are my own. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this university;
- where any part of this has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed by myself;

Signed:

Date:

ACKNOWLEDGEMENTS

This thesis would have been impossible without the input from my friends, subjects in my experiments, researchers from the ISVR or other institutions around the world. I thank you all.

Specifically, I would like to thank my supervisor Michael J. Griffin, whose much appreciated leadership, encouragement and advice allowed me to navigate my way through the difficulties of completing a Ph.D. Similarly, I owe a major debt of gratitude to Miyuki Morioka, who helped at all stages: Without her I could neither have started nor have completed this thesis.

I would also like to thank all members of the Human Factors Research Unit, especially the fantastic technicians, the great secretaries and Sue Ann Seah, for their irreplaceable help and advice.

Finally, I would like to thank my mother Baharistan C. Forta, my father Hulki Forta, and my sister Z. Özgün Forta, for being such a wonderful family.

******

"We feel that even when all possible scientific questions have been answered, the problems of life remain completely untouched. Of course there are then no questions left, and this itself is the answer."

Ludwig Wittgenstein, Tractatus Logico-Philosophicus, 6.52

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CHAPTER 1: INTRODUCTION

1.1. GENERAL INTRODUCTION

Perception of vibration is a common occurrence in the life of humans living in an industrial or post-industrial society. Passing vehicles make houses vibrate, which is perceived by the inhabitants. Computers, fans and machinery make indoor surfaces such as desktops vibrate perceptibly. Drivers and passengers feel their vehicles' floors, seats and steering wheels and rods vibrate. Manual workers are exposed to high doses of vibration when they operate power-tools. For entertainment, both children and adults use video game controllers which vibrate.

Research tends to focus on discomfort and physical harm caused by exposure to vibration, especially since hand-input vibration may cause a disorder called Hand Arm Vibration Syndrome (HAVS) and whole-body vibration and shock may cause pain in the lower back and other parts of the body. However, vibration exposure is not always unwanted, as it can also be a source of comfort, information or entertainment.

A large body of information has been gathered on the perception of vibration in the twentieth century, and continues to be gathered today. However, because human vibrotactile sense is not as dominant as vision or hearing, perception of vibration was not investigated as much as the other two named sensory systems. Consequently, not all aspects of vibrotactile perception are as well-known as those of hearing or vision and current understanding is insufficient to resolve a number of issues.

There are two basic types of intensity-related psychophysical thresholds of perception of vibration: the absolute thresholds, and the difference thresholds. The absolute threshold is the smallest magnitude of vibration that can be perceived, and the difference threshold is the smallest change in the magnitude of a vibration that can be perceived (Griffin 1996). Currently, the absolute thresholds are better understood than the difference thresholds, especially for hand-transmitted vibration. Research on both types of thresholds is continuing as well as research on other aspects of vibration perception, such as the equivalent comfort contours, and there is scope for further advances in all areas.

1.2. OBJECTIVES OF THE THESIS

The aim of the present thesis is to advance the understanding of the perception of vibration intensity differences. While various aspects of vibration difference thresholds are not well known, the focus of the thesis is on the effects of input location, excitation area, vibration frequency, vibration magnitude, masking, and somatosensory channel mediation on difference thresholds. Locations of vibration sensation and inter- and intra-subject variances of the difference thresholds were also investigated in different experiments. These factors are discussed to provide a clearer picture of the perception of vibration differences, which then led to a conceptual model.

1.3. APPLICATIONS OF THE RESEARCH

In addition to its pure scientific value, research culminating in a better understanding of vibration difference thresholds would inform future applications, especially in the fields of transportation and man-machine interface.

For instance, in order to improve the vibration comfort of a means of transport, it is useful to know how much the overall vibration magnitude (or vibration magnitudes at various input points) needs to be altered for the improvement to be noticeable by the passenger or the driver. Any change in vibration magnitude which remains below the difference threshold would not be noticed, and can be assumed to be ignored in assessment of comfort.

The design of tactile interfaces which communicate with the user via vibration would also benefit from a better understanding of tactile difference thresholds. Tactile feedback is useful in cases where information from other sensory systems are limited, or where a supplement to information from the other systems is needed. Tactile feedback could be particularly useful for people with impaired vision or hearing, as well as in virtual reality applications.

1.4. ORGANISATION OF THE THESIS

The thesis is composed of an abstract, ten chapters, references and four appendices.

- Abstract
- Chapter 1: Introduction
- Chapter 2: Literature Review
- Chapter 3: Method

- Chapter 4: Difference thresholds of whole-body vibration (Experiment I)
- Chapter 5: Difference thresholds of hand-transmitted vibration (Experiment II)
- Chapter 6: Difference thresholds of foot-transmitted vibration (Experiment III)
- Chapter 7: Masked difference thresholds (Experiment IV)
- Chapter 8: Difference thresholds with local vibration (Experiment V)
- Chapter 9: General discussion
- Chapter 10: Conclusions
- References
- Appendix A: Instructions (instructions for the subjects)
- Appendix B: Difference threshold data (difference threshold data form the experiments)
- Appendix C: Sample Matlab scripts (used for data analysis)
- Appendix D: Questionnaires (used for health screening and data collection)

1.5. THE EXPERIMENTS

To achieve the objectives of the thesis, five experiments were conducted:

- Experiment I measured the difference thresholds for vertical (z-axis) whole-body (seat-input) sinusoidal vibration at eight frequencies from 2.5 to 315 Hz, using three different magnitudes at each frequency. Location of vibration perception data was also collected in Experiment I.

- Experiment II measured the absolute and difference thresholds for vertical (x-axis) hand-transmitted sinusoidal vibration at 16 Hz and 125 Hz, using a grasping posture. The difference thresholds were obtained at six different magnitudes at each frequency.

- Experiment III was similar to Experiment II, as it measured the absolute and difference thresholds for vertical (x-axis) foot-transmitted sinusoidal vibration at 16 Hz and 125 Hz. The difference thresholds were obtained at six different magnitudes at each frequency. Experiment III also calculated data on the location of perception of vibration.

- Experiment IV measured the difference thresholds for vertical (x-axis) hand-transmitted 125-Hz sinusoidal vibration masked by narrow-band random vibration centred on 16 Hz, with a grasping posture. The absolute thresholds for both stimuli were also measured. The measurements were repeated six times for every condition in Experiment IV.

- Experiment V obtained the absolute and difference thresholds using vertical (x-axis) sinusoidal vibration with two different contact conditions at the thenar eminence of the hand and the volar forearm.

CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

Psychophysics is the “scientific study of the relation between the stimulus and the sensation” (Gescheider, 1985). The ‘psycho-‘ part of the term signifies the psychological (the subjective sensation) part of the relation, and ‘-physics’ relates to the stimulus side of the relation (the objective magnitude). In human perception of vibration, the physical stimuli are vibration signals and the sensations are the response of the nervous system to these signals.

Humans have a highly developed somatic sense which allows them to detect vibration stimuli. The somatosensation is a multimodal sensory experience unlike most other sensory modalities. It produces a wide range of sensations from pain to thirst and from hunger to sexual arousal. This multitude of sensation modes arises from different receptor types involved in the process. Nocireceptors produce the sensation of pain, proprioceptors produce information about the location of body parts, thermal receptors create the sensations of cold and warmth, and various types of mechanoreceptors create the remaining aspects of the sensation of touch. The mechanical aspect of somatosensation mediated by the mechanoreceptors is called ‘taction’ (Gescheider, 1985, 1997b).

The sense of touch has two components, active (haptic) touch and passive touch. Active touch defines the action when a person probes the shape, texture and firmness of an object, i.e. manipulative and exploratory behaviour. Passive touch, on the other hand, is the sensation which occurs when an object is pressed against the subject’s skin (Schiff and Foulke, 1982).

2.2. PHYSIOLOGY OF VIBRATION PERCEPTION

Vibration is a mechanical phenomenon and is detected by the mechanoreceptors in the skin and mediated by the somatosensory channels related to these mechanoreceptors.

The mechanoreceptors are found in all skin tissue, with different areas of the skin having varying density and combinations of mechanoreceptors. Tissues other than the skin in the human body also have mechanoreceptors. Neurophysiological investigation led to the discovery of four types of nerve fibres innervating the glabrous skin. Studies detailing the characterization of various mechanoreceptors include Johansson (1976, 1978), Johansson and Vallbo, (1979, 1980, 1983), Knibestol and Vallbo (1970), Mountcastle et al. (1969), Talbot et al. (1968), Vallbo and Johansson (1984).

Four types of mechanoreceptors are found in the glabrous skin (i.e. the hairless skin of the palm and the sole of the foot) of humans:

a. Meissner corpuscles
b. Pacinian corpuscles
c. Merkel discs
d. Ruffini endings (existence disputed)

In addition to the mechanisms of the glabrous skin, the following afferents innervate the hairy skin of mammals (Mountcastle, 2005):

e. Pacinian corpuscles
f. Merkel discs
g. Ruffini endings
h. Hair follicles (G-1, G-2 and D hairs)
i. C-mech, C-fiber skin surface unencapsulated
j. Field skin surface

Figure 2.1 summarises the adaptation properties, relative innervation densities and the typical receptive field sizes of the four mechanoreceptors found in the glabrous skin of the hand. Each of the mechanoreceptors of the glabrous skin is associated with a somatosensory channel (and a primary afferent nerve fiber type) as follows:

a. Meissner corpuscles – Non-Pacinian I (Fast Adapting I)
b. Pacinian corpuscles – Pacinian (Fast Adapting II)
c. Merkel discs – Non-Pacinian III (Slow Adapting I)
d. Ruffini endings – Non-Pacinian II (Slow Adapting II)

According to Mountcastle (2005) these ‘channels’ or ‘systems’ refer to “first-order afferents and the central pathways over which they project through the transition nuclei of the brain stem and thalamus and into the somatosensory cortex”.

The following review of the mechanoreceptors is compiled from other reviews found in Cauna (1960), Johansson and Vallbo (1983), Griffin (1996), Pasterkamp (1999), Morioka (2001), Roberts (2002), Mountcastle (2005) and Gescheider *et al.* (2009).

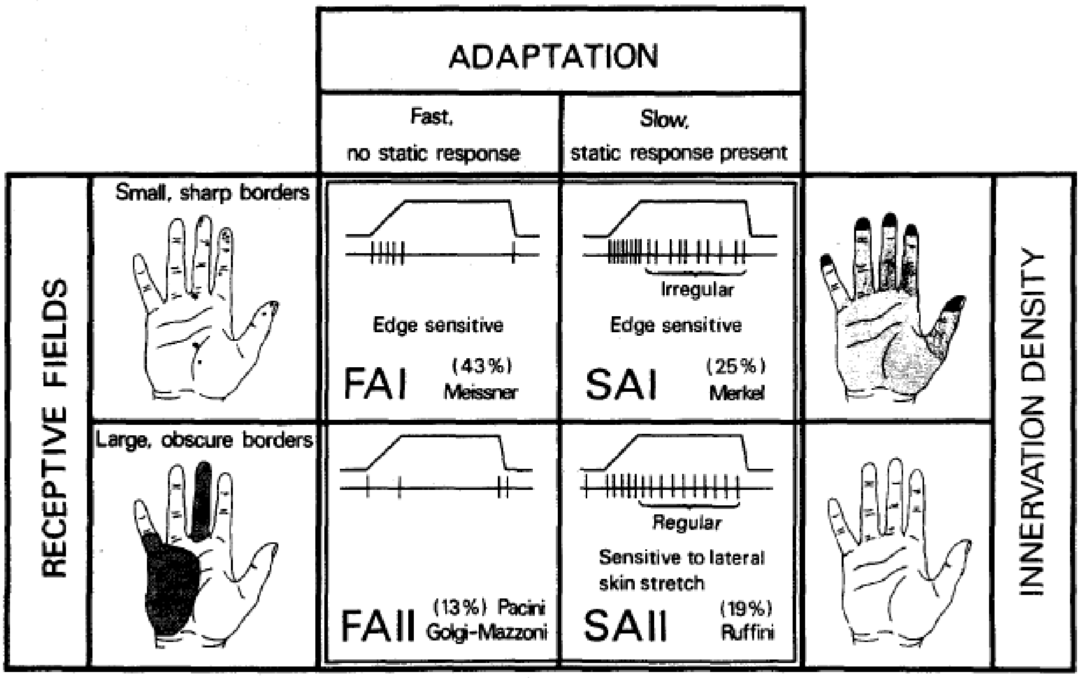


Figure 2.1. The adaptation properties, relative innervation densities and the typical receptive field sizes of the four mechanoreceptors found in the glabrous skin of the hand. Image from Signals and Perception the Fundamentals of Human Sensation. (Roberts, 2002, originally from Westling, 1986)

Humans and macaque monkey hands have virtually identical vibration detection and discrimination capabilities, but monkey hands lack the SAII afferents (Mountcastle, 2005).

2.2.1. Meissner corpuscle

The Meissner corpuscles are found in the dermis, close to the surface of the skin (Figure 2.2). The Meissner afferents adapt rapidly to a stimulus, which means that they signal the changes in stimulus intensity, rather than the sustained stimulus. They have well-defined receptive fields of approximately 5-mm diameter. Meissner corpuscles mediate the absolute threshold for vibration in the 3 – 40 Hz frequency range. Meissner corpuscles compose 43% of the mechanoreceptors in the skin of the hand, but they are not found in the hairy skin.

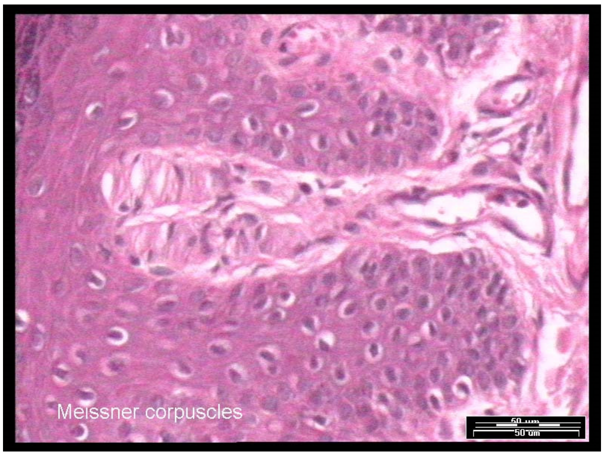


Figure 2.2. Meissner corpuscle in dermis (image taken from http://www.technion.ac.il/~mdcourse/274203/slides/Nerve/Receptors/6-Meissner%20corpuscles.jpg).

The Meissner corpuscles are innervated by the rapidly adapting fibres of the NPI channel (Cauna and Ross, 1958, Lindblom, 1965, Lindblom and Lund, 1966, Talbot *et al.*, 1968, Mountcastle *et al.*, 1972). Branches of rapidly adapting axons divide further to innervate as many as 25 Meissner corpuscles, while some Meissner corpuscles are innervated by more than one axon.

2.2.2. Pacinian corpuscle

Pacinian corpuscles are innervated by rapidly adapting fibres like the Meissner corpuscles (Mountcastle *et al.*, 1972; Bolanowski and Verrillo, 1982). Due to its structure of cellular lamellae, the Pacinian corpuscle acts as a high-pass mechanical filter, mediating the absolute thresholds for sinusoidal stimuli for frequencies above about 40 Hz.

Pacinian afferents have sensitive fields of the order of centimetres diameter, without well-defined borders. Pacinian corpuscles are found in the subcutaneous tissues as well as the deeper layers of the skin (Figure 2.3). They are also found in hairy skin, and in body tissues other than the skin, such as tendons.

The Pacinian channel sensitivity is dependent on stimulus duration and the area of excitation, as well as the age of the subject.

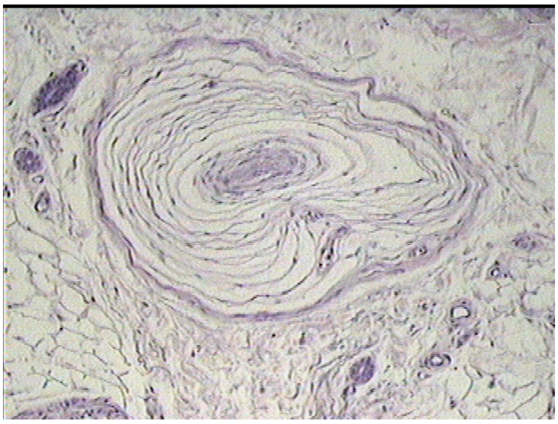


Figure 2.3. Pacinian corpuscle, image from http://www.dmacc.edu/Instructors/pacinian.htm

Pacinian corpuscles are about 13% of the mechanoreceptors in the skin of the hand.

2.2.3. Merkel's disc

Merkel's discs are innervated by slowly adapting afferents. They are located at the border of dermis and epidermis of glabrous skin. Merkel's discs' afferents have well-defined receptive fields in the order of millimetres. They are sensitive to gradient stimuli and are sensitive in two-point discrimination tasks. Phillips and Johnson (1981) found that placing a finger on the edge of an object results in spike rates in SAI fibres that are 20 times faster than when placing the finger on a smooth surface.

Merkel's discs respond to a wide range of frequencies, but determine the absolute threshold at the hand at frequencies below about 3 Hz (Figure 2.8).

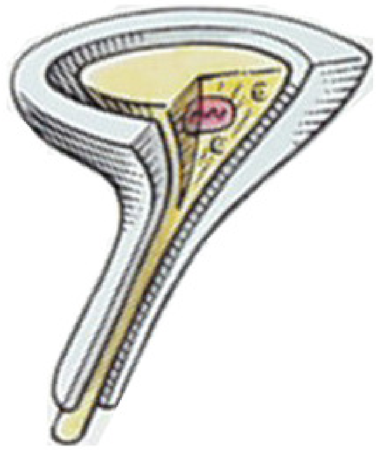


Figure 2.4. Structural diagram of Merkel's disc, image from http://www.dkimages.com/discover/Home/Health-and-Beauty/Human-Body/Nervous-System/Unassigned/Unassigned-05.html

About 25% of the mechanoreceptors in the skin of the hand are Merkel's discs.

2.2.4. Ruffini endings

Ruffini endings are innervated by slowly adapting afferents found in the dermis layers (Figure 2.5). They are believed to have receptive fields in the order of centimetres, with indefinite boundaries like the Pacinian corpuscles. Ruffini endings are sensitive to lateral stretching of the skin. Ruffini endings are sensitive to a similar frequency range as the Pacinian corpuscles.

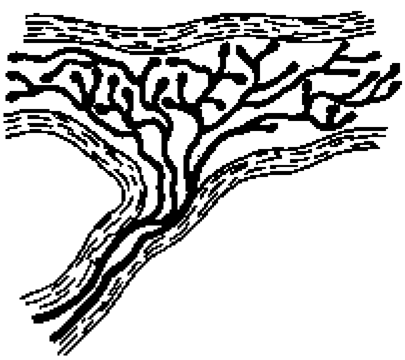


Figure 2.5. Drawing of a Ruffini ending from http://library.thinkquest.org/05aug/00386/touch/ruffiniending.gif

Ruffini endings are 19% of the mechanoreceptors in the skin of the hand. Ruffini endings are the least known of the four corpuscles, and their existence in the glabrous skin and connection with the SAII afferents has been questioned by some researchers (Pare et al., 2003).

2.2.5. Neural pathways to the somatosensory cortex

Figure 2.6 shows the schematic outline of the order of neuronal operations leading from stimulus to perception.

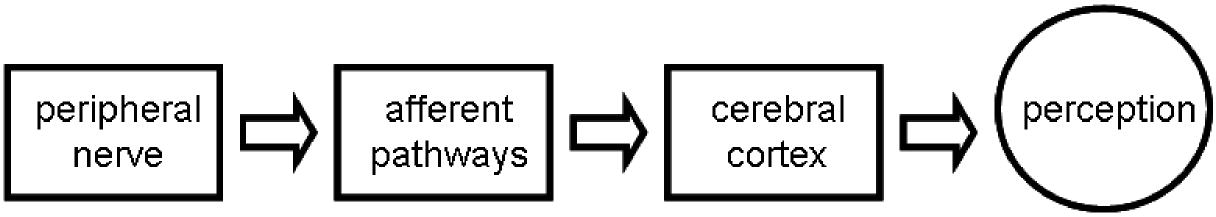


Figure 2.6. Order of neuronal operations leading from stimulus to sensation (reproduced from Mountcastle 2005).

While the mechanical deformation of the skin is detected by the mechanoreceptors, the sensation of touch is created at higher levels of the nervous system. The mechanoreceptors themselves are specialised nerve endings. The bodies of the nerves connected to the mechanoreceptors are located in structures called the ‘dorsal root ganglia’ (Figure 2.7) (Roberts, 2002).

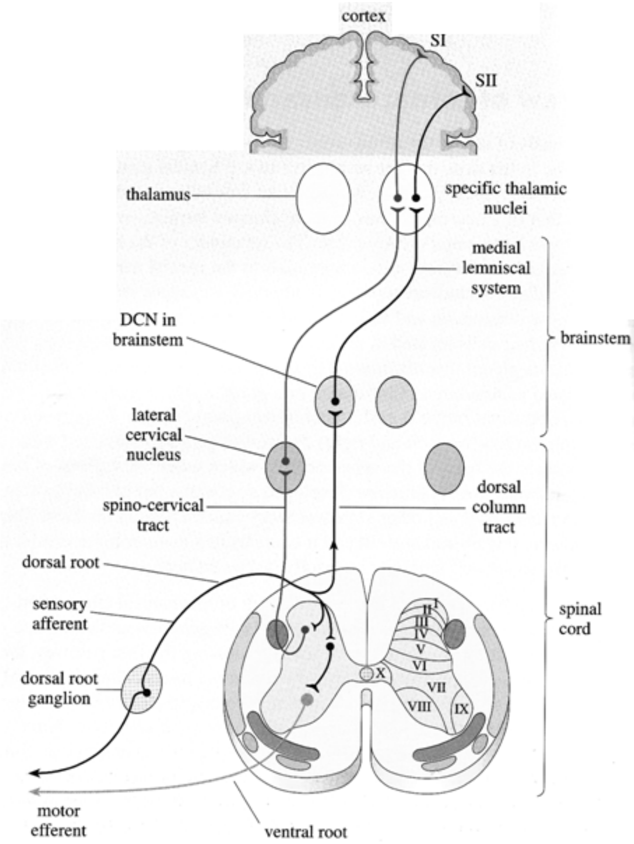


Figure 2.7. Basic somatosensory pathway between the dorsal root ganglion and the somatosensory areas in the cortex, taken from Roberts, 2002 (DCN: Dorsal Column Nucleus).

Following the nerve pathway, the vibration information is transmitted from the receptor at the skin to the dorsal root ganglia. The nerves then synapse in the spinal cord, and from there the touch-related information is carried to the somatosensory cortex in the brain through one of two possible pathways: The spinopthalmic pathway, which carries most of the touch related information, and the dorsal-column-medial-lemniscal (DCML) pathway which is faster than the spinopthalmic pathway, and carries information needed for rapid movements that require quick feedback (Wolfe et al., 2006).

From the spinal cord pathways, the information is transmitted first to the medulla, and then to the thalamus, before reaching the specialised areas in the cortex (somatosensory area 1 and somatosensory area 2). Vibration sensation enters the consciousness at these two somatosensory areas of the cortex.

Diagrammatic outlines of somatic afferents do not show the connections between individual systems and other brain systems so they may be misleading. Overlap occurs, especially in the thalamus and the cortex (Mountcastle, 2005).

2.3. ABSOLUTE THRESHOLDS

Measurement of perception is possible by employing the concept of the sensory threshold. Herbart in 1824 described the threshold by assuming that mental events need to be stronger than a certain amount in order to be consciously experienced. Later, psychophysicists such as E.H. Weber and G.T. Fechner devised methods to measure the sensitivity limits of the human sense organs. (Gescheider, 1985)

The thresholds were defined in terms of the smallest stimulus energy detected by the sense organ. However, the sensitivity of the organism varies over time. Due to this variance in sensitivity, the threshold cannot be defined as a single number, above which detection always occurs and below which detection never occurs. So, in psychophysics, the threshold is normally a statistical concept. The ratio of 'detection' to 'no detection', used in determining the threshold, changes from researcher to researcher. In the past, it was typically defined as the stimulus value which can be detected 50% of the time. Recent research tends to determine the threshold at higher detection rates, usually 75% or above.

An 'absolute threshold' is defined as the "value of a stimulus which is just sufficient for its presence to be detected". The absolute threshold is not a unique value, but can only be defined by statistics, indicating the probability of detection for a given value of the stimulus, as explained above (Griffin, 1996). Absolute thresholds of the four somatosensory channels of the glabrous skin, may vary with varying frequency, stimulus duration, excitation area, input location, gradient, age or skin temperature depending on the characteristics of the individual channels.

The absolute threshold can be determined either by first-order afferent fibres or by higher-order central neural operations such as spatial summation (Mountcastle, 2005).

2.3.1. Multi-channel models of vibration perception

Studies designed to obtain frequency-dependent curves for absolute thresholds of vibration started in the 1930s with von Bekesy (1939). Since then, many such frequency-dependent curves of vibration detection thresholds have been obtained from experiments conducted on the glabrous skin of the hand.

Sherrick investigated the variables affecting the sensitivity to vibration of the skin in 1953, and Verrillo *et al.* developed the duplex model of vibration perception in the 1960s. The two channels in the model were named the Pacinian and the non-Pacinian. Gescheider *et al.* (1978) also investigated the duplex model.

The duplex model was improved by Capraro *et al.* (1979), by dividing the non-Pacinian system into two channels, thereby developing the triplex model. Gescheider *et al.* (1985) detailed the triplex model.

Finally, Bolanowski *et al.* proposed a four-channel model in 1988. In this model, another non-Pacinian channel, which determined the threshold at high frequencies when the Pacinian channel was bypassed, was added to the triplex model. Gescheider *et al.* (2001) confirmed the thresholds in the four-channel model of Bolanowski *et al.*, using an ‘adaptation tuning curve’ technique. Figure 2.8, taken from Bolanowski *et al* (1988), shows the absolute thresholds of the four somatosensory channels found in the glabrous skin. The curves show the thresholds in displacement as a function of frequency. Thresholds of the NPII and NPIII channels, where they are normally above the thresholds of P and NPI, and therefore not observed directly, were obtained through experiments in which the P and NPI channel responses were masked.

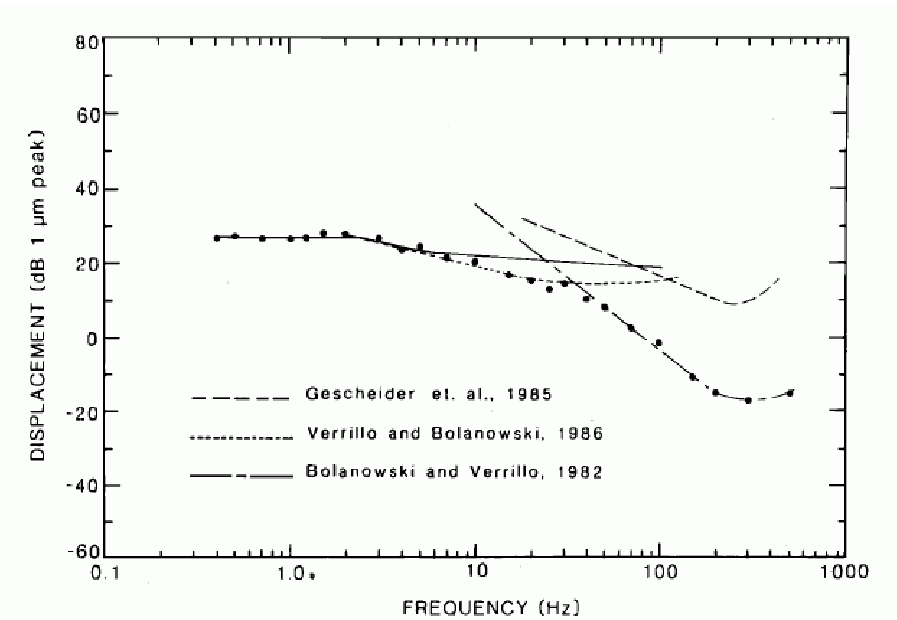


Figure 2.8. The four-channel model from Bolanowski et al. 1988. The solid line shows the NPIII, dotted line NPI, dashed line NPII, and the dash-dot line P channel.

The thresholds shown in Figure 2.8 were obtained by experiments performed on the glabrous skin of the hand. The thresholds obtained under different conditions (e.g. with different contact conditions) would be different from the plotted thresholds.

The four somatosensory channels described in the four-channel model were matched to the mechanoreceptors in the glabrous skin as explained in Section 2.2.

Under normal conditions, the sensory receptors in peripheral tissues are understood to act like frequency filters often selectively tuned to special features and to limited quantitative ranges of stimulus parameters (Mountcastle, 2005), defining the observed ‘channel’ behaviour.

Despite the identification of various mechanoreceptors, channel-based models for absolute thresholds are currently not available for the hairy skin.

2.3.2. Effect of frequency

Many studies either directly investigated the effect of vibration frequency on absolute thresholds or employed vibrations with various frequencies in investigations of factors other than frequency. These studies resulted in the development of multi-channel models of vibration perception discussed in the previous section.

Studies investigating the effect of vibration frequency on vibration thresholds found that the vibration sensitivity is highly dependent on frequency up to 1000 Hz. In terms of displacement, the sensitivity increases until about 250 Hz and then starts to decline, defining a U-shape, which is typical of the P channel. Figure 2.9 shows the frequency-dependence of hand-input vibration obtained from 12 independent studies.

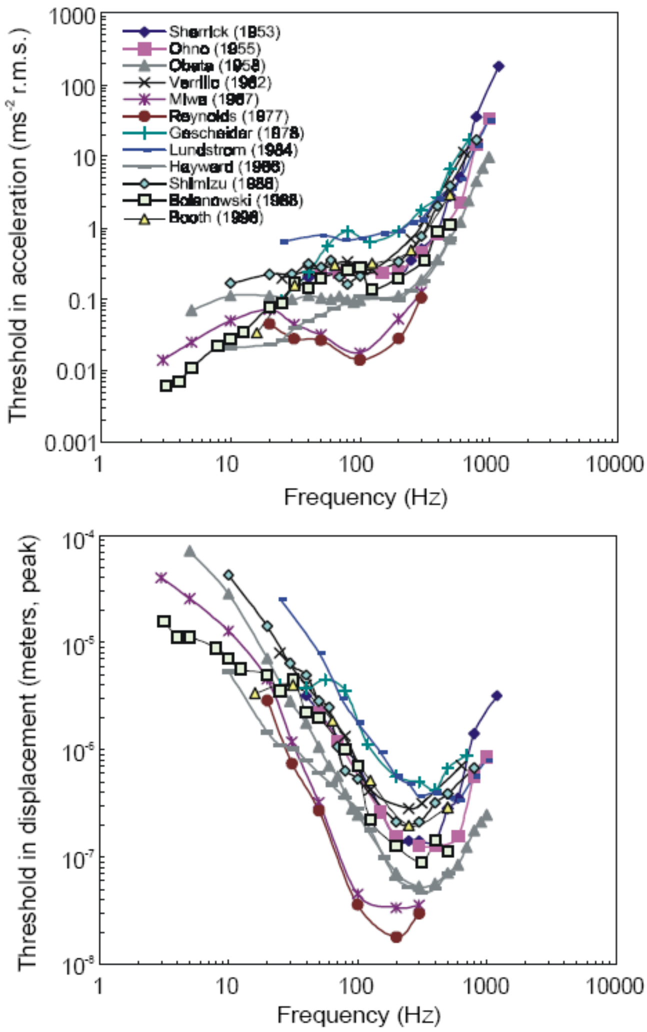


Figure 2.9. Comparison of the studies on the effect of frequency on hand-input vibration from Morioka (2001).

Absolute thresholds for whole-body vibration and foot-transmitted vibration have a frequency-dependence pattern similar to the hand-input vibration.

More recently, a study by Morioka and Griffin (2008b) measured the absolute thresholds for hand, foot, and whole-body vibration from 8 to 315 Hz (for the hand and the foot) and 2 to 315 Hz (for the whole body). This study found a U-shaped acceleration contour for all three locations at frequencies greater than approximately 80 Hz, suggesting that the P channel was responsible for mediating the perception of the vibration stimuli for all three locations.

2.3.3. Effect of contact area

Researchers have investigated the dependence of the absolute thresholds on contact area using psychophysical methods.

A study by Verrillo in 1963 detailed the effect of contact area on vibration thresholds. Verrillo tested the absolute thresholds of three subjects at seven vibration frequencies (25, 40, 80, 160, 250, 320, 640 Hz) with seven different contactor sizes (0.005, 0.02, 0.08, 0.32, 1.3, 2.9 and 5.1 cm^2). The contactors were round in shape and they were separated from the surround by a 1-mm gap. The exact location of the contactor was the fleshy pad of the palm over the first metacarpal of the right hand.

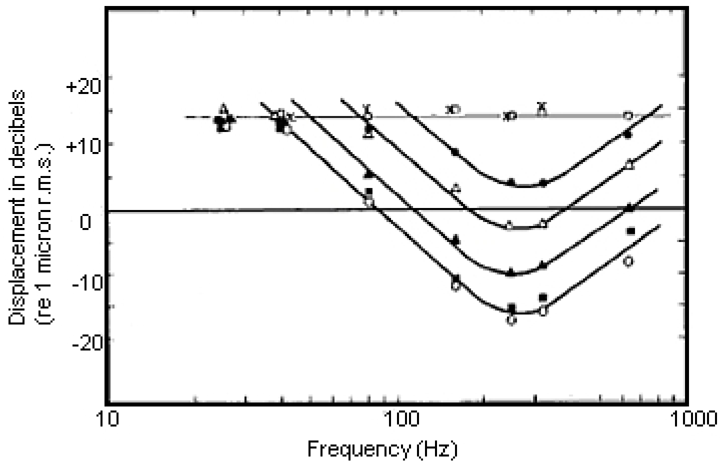


Figure 2.10. The effect of contact area on vibrotactile thresholds from Verrillo (1963). Contactor areas are: x 0.005 cm^2; open squares 0.02 cm^2; closed circles 0.08 cm^2; open triangles 0.32 cm^2; closed triangles 1.3 cm^2; closed squares 2.9 cm^2; open circles 5.1 cm^2.

The findings of the study are plotted in Figure 2.10. Each curve shows the threshold in displacement in decibels (re: 1 micrometre) obtained at seven frequencies using one of the seven test contactors. The curves show a U-shaped trend at higher frequencies, with the larger contactors producing the lower thresholds. At lower frequencies, however, there is no difference between the thresholds obtained by different contactors.

Verrillo concluded that the absolute thresholds for vibration plotted as a function of area yielded a slope of approximately 3 dB reduction per doubling of area at frequencies above 40 Hz. However, at low frequencies, the absolute threshold was independent of contactor size and for very small contactors the threshold was independent of frequency. These findings constituted evidence for a two-channel perception system, with the Pacinian system mediating the threshold above 40 Hz, and the non-Pacinian system mediating the threshold below 40 Hz.

Another study by Verrillo in 1965 tested the absolute thresholds of a small number of subjects (four or five depending on experiment). The variables tested were the stimulus duration, contact area, and frequency. In total, eight frequencies from 2 Hz to 200 Hz were tested. The contactor areas were 0.005 cm^2, 0.02 cm^2, 0.32 cm^2 and 2.9 cm^2.

The results in Figure 2.11 show the absolute threshold reducing with increasing contact area at higher frequencies when the larger contactors are used, but they stayed constant when the smallest contactor was used.

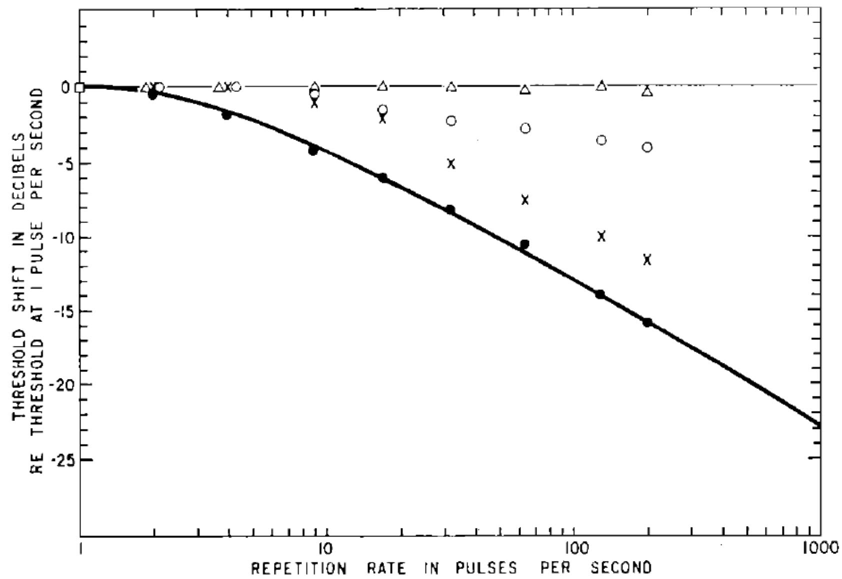


Figure 2.11. The effect of contact area from Verrillo 1965. Contactor areas are: triangles 0.005 cm^2; open circles 0.02 cm^2; x 0.32 cm^2; closed circles 2.9 cm^2.

There were similar findings in later studies by Verrillo (1966, 1985). Studies by other researchers also agree on the thresholds reducing with increased area above about 40 Hz, when the threshold is mediated by the Pacinian channel (Morioka, 2001; Morioka and Griffin, 2004).

There are two possible mechanisms for spatial summation, one is ‘neural integration’ which involves the determination of the threshold at a higher level of the central nervous system using the information from numerous individual receptors. The second mechanism is called the ‘probability summation’ which involves reduction of the absolute threshold as more sensitive individual receptors are excited with increasing excitation area (Gescheider *et al.*, 2009). Psychophysical studies suggest that both mechanisms are involved in the spatial summation ability of the P channel (Gescheider *et al.* 2005; Güçlü *et al.*, 2005).

2.3.4. Effect of surround

Another factor affecting the perception of vibration is the existence of a rigid surround around the contactor.

Verrillo (1962) observed that hand-transmitted thresholds were affected by the presence of a surround. This study employed a single contactor 0.113 cm^2 in size and five different surround gaps corresponding to 0.365, 0.672, 1.49, 2.38, 4.86 cm. The excitation was input to the first metacarpal of the right thumb. It was found that the thresholds at low frequencies (25 and 50 Hz) increased with increasing surround area, but at high frequencies (250 and 320 Hz) the thresholds were reduced with increasing surround area. A study by van Doren (1990) also investigated the effect of the surround on perception thresholds and found similar results.

A later study by Gescheider *et al*. (1978) compared the effect of the presence and the absence of a surround with two contactors 0.2 and 3.0 cm^2 in area. It was observed that the introduction of a surround increased the thresholds above about 60 Hz, but reduced them below that frequency. While the thresholds kept increasing below 60 Hz when there was no surround, they remained constant when the surround was used.

A study by Lamore and Keemink (1988) determined the absolute thresholds at the hand in the range between 5 to 1000 Hz. Three input locations were tested, the first phalanx of the middle finger, the thenar eminence and the inner side of the forearm. They also tested the effect of a rigid surround combined with the effect of contact force. Four subjects were tested twice to obtain the curves in the latter experiment. The contactor area in the experiments was 1.5 cm^2. On the effect of surround, the authors concluded that in the very low-frequency region, without a rigid surround the vibration threshold increased with increasing static force.

A study by Harada and Griffin (1991) tested the effect of various conditions on the absolute thresholds. The vibration was input to the middle fingertip of the left hand of five subjects. A contactor with a 7-mm diameter was used with three different gap sizes and three different contact forces (1, 2 or 3 N). Temperature and temporary threshold shift effects were also investigated. The vibration stimuli used in the experiments were in the range (16 Hz to 500 Hz). It was found that a surround around the contactor greatly reduced the absolute thresholds at 16 and 31.5 Hz, but increased the absolute thresholds at 125, 250 and 500 Hz.

Morioka (2001) also measured the effect of surround, at the fingertip of 12 subjects. The contactor had a diameter of 6 mm, and the gap between the contactor and the surround was 2 mm. The contact force was 1 N. It was found that the absolute thresholds in acceleration were greatly reduced when the surround was used at frequencies below 60 Hz. About 60 Hz, thresholds did not depend on the use of the surround. At frequencies above 60 Hz, however, the thresholds with the surround were higher than the no-surround thresholds. The results are shown in Figure 2.12.

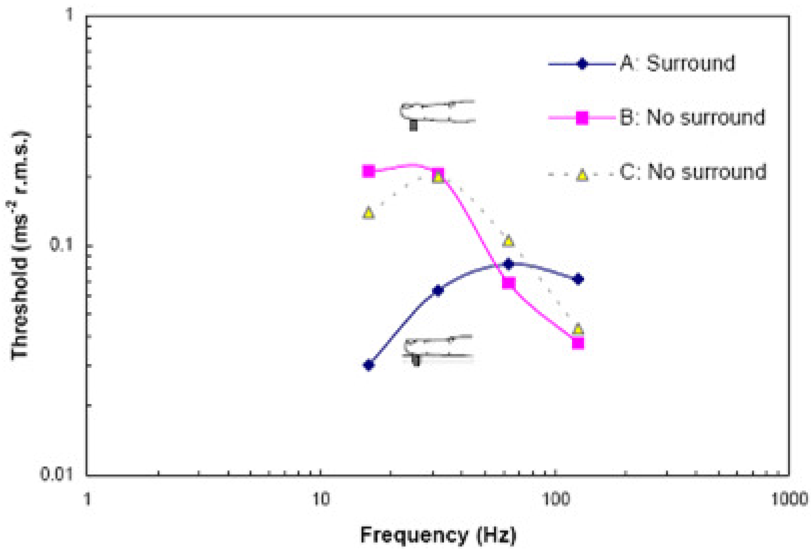


Figure 2.12. The effect of surround on absolute thresholds from Morioka (2001).

The effects of the surround on absolute thresholds are explained by the existence of two separate channels mediating the threshold under the tested conditions, namely the Pacinian at high frequencies and the Non-Pacinian I (NPI) at lower frequencies. Introduction of a surround therefore raises the P thresholds due to the surround inhibiting the area summation capability of the P channel, but it lowers the NP thresholds because of that channel's sensitivity to gradient stimuli.

2.3.5. Effect of contact force

Findings from the studies on the effect of contact force on absolute vibration thresholds indicate that the thresholds are decreased as the contact force increases, especially for higher frequencies.

The Lamore and Keemink (1988) study described in Section 2.3.4 above, concluded that with increasing contact force the sensitivity in the high-frequency region (around 200 Hz) increases, while it decreases at low frequencies (5 Hz up to 30 Hz). They identified a crossover frequency about 30 Hz. The frequency-dependence of thresholds was not observed when there was minimal contact between contactor and skin, irrespective of site of stimulation, contactor size, and the presence or absence of a rigid surround. The possibility of the observed constant threshold being determined by “a separate receptor system” was suggested.

The Harada and Griffin (1991) study found an effect of the contact force at higher frequencies of 125, 250, and 500 Hz. At these frequencies, the thresholds were lower with higher contact force.

Other studies of the effect of contact force on hand-transmitted vibration that also found decreasing thresholds with increasing contact force include Green and Craig (1974), Lowenthal and Hockaday (1987) and Makous *et al.* (1996).

2.3.6. Effect of input location

Vibration absolute thresholds are dependent on the input location and contact conditions. As explained in the section on mechanoreceptors, the somatosensory channels have varying characteristics, depending on the neuro-physical characteristics of individual mechanoreceptors, resulting in channel capabilities such as spatial summation and temporal summation. Given the fact that the distribution and density of mechanoreceptors in the skin vary on the location, the thresholds also vary.

Morioka and Griffin (2008b) tested the absolute thresholds for three directions at three input locations, the hand, the foot, and the seat. It was found that the vertical vibration at the seat provided the greatest sensitivity at frequencies between 8 and 80 Hz, whereas vertical vibration at the hand provided the greatest sensitivity at frequencies above 100 Hz. Comparison of the median thresholds for vibration at the three locations are given in Figure 2.13.

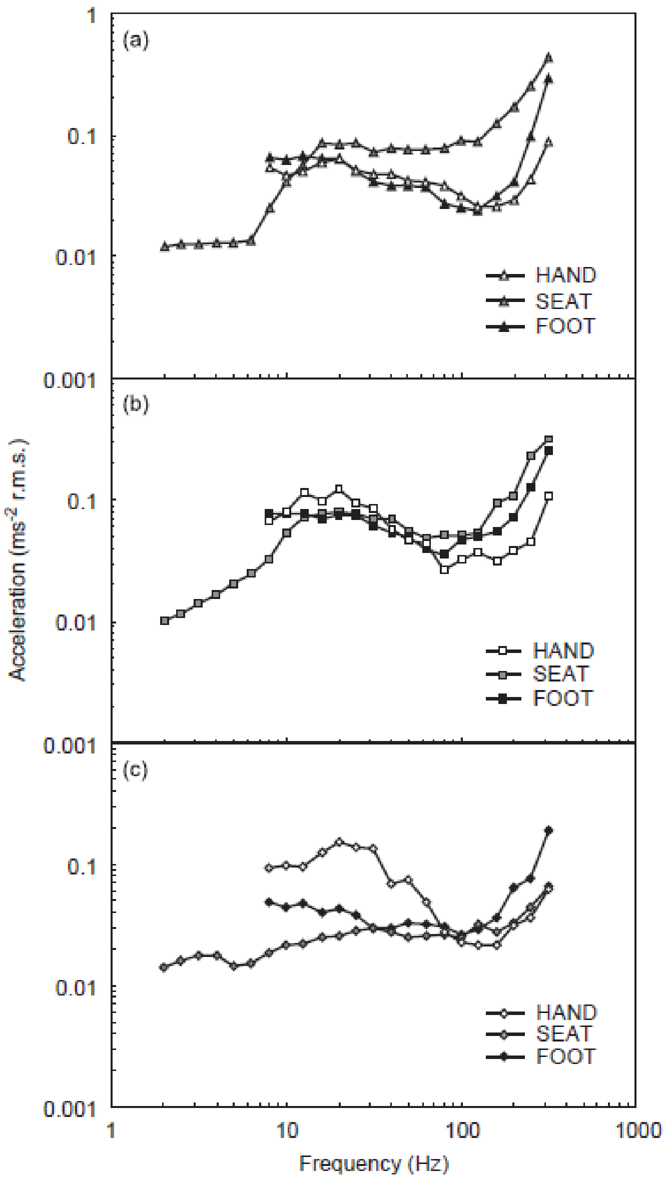


Figure 2.13. Median absolute thresholds by frequency for vibration input to the hand, feet and seat from Morioka and Griffin (2008b), in three vibration directions: (a) fore-and-aft; (b) lateral; (c) vertical.

2.3.6.1. Hand-input vibration

Vibration thresholds at the hand are well-known compared to the other parts of the body. Evaluation of hand-transmitted vibration can be found in studies by Miwa (1967a, 1967b, 1967c), and Griffin (1996), or in standards such as ISO 5394-1 (2001).

Some studies investigated the differences in the vibrotactile sensitivity within the hand. Lofvenberg and Johansson (1984) tested seven different locations in the hand using sinusoidal stimuli and 11 subjects. The tested frequency range was 0.8 to 400 Hz. It was found that, generally, the distal part of the distal phalanx was the most sensitive location, followed by the proximal part of the distal phalanx, the thenar eminence and the mid palmar. The differences between the locations were “most pronounced” at frequencies below 40-60 Hz. Interregional variation was lower at higher frequencies. These differences were attributed to the varying density of afferent mechanoreceptive units.

As described in the above section, the Lamore and Keemink (1988) study also tested the effect of location. It was concluded that the minimum thresholds attributed to the Pacinian systems at the first phalanx of the middle finger and at the thenar eminence were equal (-30 dB re 1 µm r.m.s.). However, the lowest threshold for the inner forearm was greater. This was ascribed to the density of the Pacinian receptors being lower in the hairy skin of the forearm.

2.3.6.2. Foot-input vibration

Studies on foot vibration are rarer than studies on hand vibration. Many studies about foot vibration are related to medical diagnostics (Vedel and Roll, 1982, Kekoni *et al*., 1989, Gu and Griffin, 2007). Absolute thresholds and equivalent comfort contours were also investigated for foot-transmitted vibration. Parsons *et al*. (1982), Rao (1983), Miwa (1988) and Morioka and Griffin (2008a) reported equivalent comfort contours for vibration of a footrest.

Morioka and Griffin (2002a) investigated the effects of boots and gender on absolute thresholds for foot-pedal vibration. No differences in the thresholds were observed between the genders. The boots had little effect on the difference thresholds (Figure 2.14).

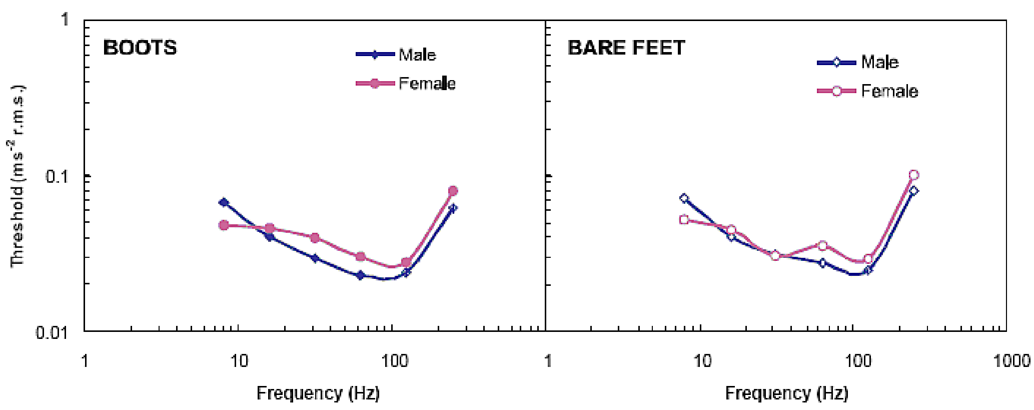


Figure 2.14. Absolute thresholds for the feet from Morioka and Griffin (2002a).

2.3.6.3. Whole-body vibration

A study by Parsons and Griffin (1988) reported a series of experiments on the perception of whole-body vibration for sitting, standing, and supine subjects. This study found that the median threshold was approximately 0.01 ms^{-2} r.m.s. between 2 Hz and 100 Hz. Supine subjects were found to be more sensitive to vibration than sitting or standing subjects.

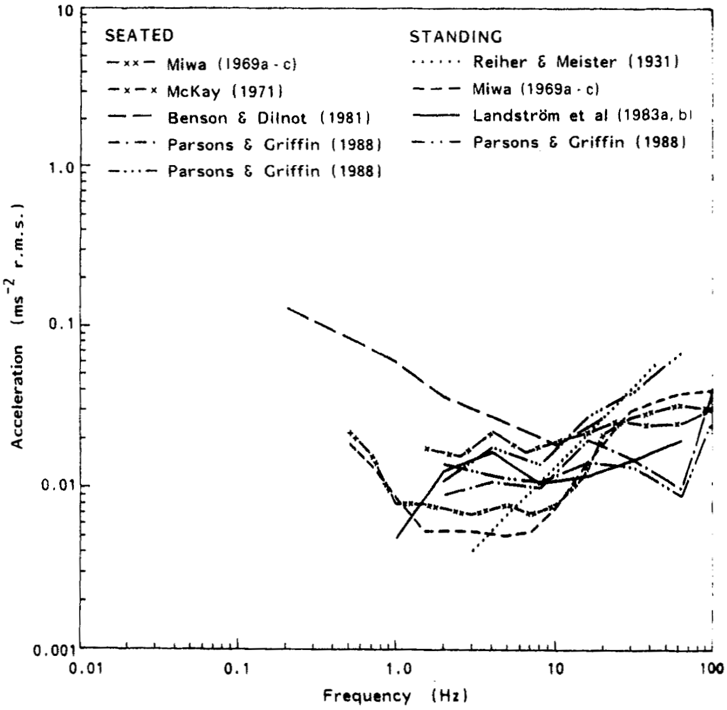


Figure 2.15. Comparisons of the median absolute threshold contours for vertical vibration of seated and standing subjects from Griffin (1996).

Comparisons of absolute thresholds for whole-body vibration of seated and standing subjects are given in Figure 2.15. The whole-body vibration thresholds are lower than those obtained from the hand, until about 100 Hz. Above that frequency, the whole-body thresholds increase. The overall shape of the threshold curve is not clearly U-shaped unlike the thresholds at the hand or the foot (see Figure 2.13).

2.3.7. Effect of input direction

A study by Morioka and Griffin (2008b) investigated the absolute thresholds for the perception of fore-and-aft, lateral, and vertical vibration at the hand, the seat, and the foot. Tested frequency ranges were 8-315 Hz at the hand and the foot, and 2-315 Hz at the seat. The vibration was input to the hand with a handle-grasping posture, and to the foot through an inclined footpad. Whole-body vibration was input through a rigid seat. Comparison of the absolute threshold contours between the three locations for three directions found in this study are given in Figure 2.16.

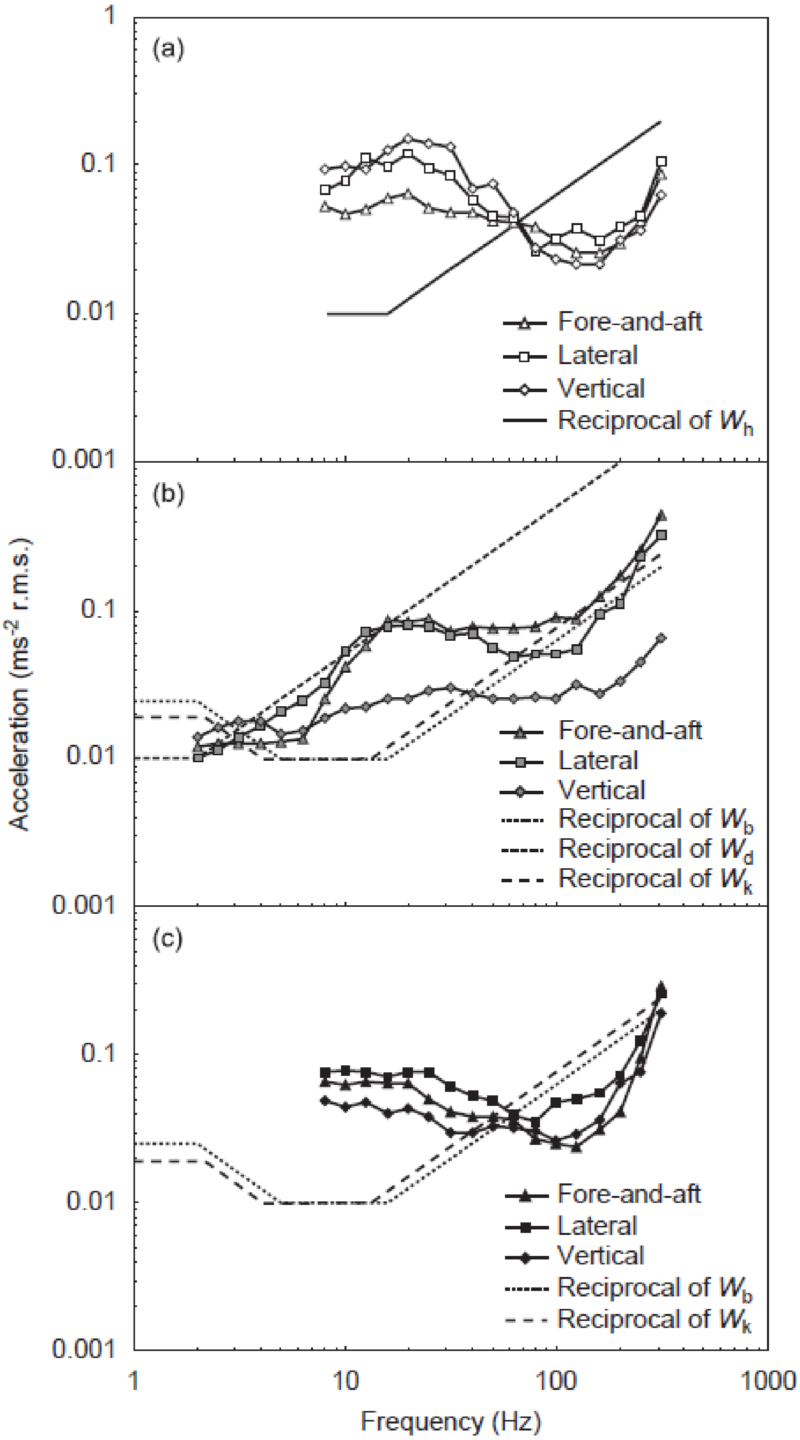


Figure 2.16. The median absolute threshold contours for the three axes for hand vibration, foot vibration, and whole-body vibration, overlaid with the reciprocals of the normalised frequency weightings from the standards, from Morioka and Griffin (2008b): (a) hand; (b) seat; (c) foot.

Figure 2.16 shows considerable differences between the reciprocals of the normalised frequency weightings from the standards and the measured absolute thresholds for hand and foot transmitted vibration. For frequencies above about 10 Hz, the subjects were more sensitive to vertical seat input vibration, compared to seat vibration in other axes.

2.3.8. Effect of stimulus duration

The study by Verrillo in 1965, described in Section 2.3.3 investigated the effect of stimulus duration on absolute thresholds. The aim of the study was to test a theory of temporal summation formulated by Zwislocki (1960), based on the assumption that “each elemental stimulus such as a pulse or a single cycle of a sinusoidal vibration produces a neural excitation which decays exponentially with time.” Employing binaural audiological data, Zwislocki modelled the summation by an integrator having a time constant of 200 ms, which results in a decrease in threshold at a rate of -3 dB per doubling of a sequence of elemental stimuli from durations between 10 to 100 ms. Zwislocki concluded that the temporal summation probably takes place in nuclei of the central nervous system.

The results for different contact and frequency conditions tested in the Verrillo (1965) study are given in Figure 2.17. Stimuli at 100 Hz, 250 Hz, and 500 Hz were used in the tests, with contactors of 0.02, 0.05, 0.08 and 2.9 cm^2 in area. It is visible from the results that for large contactors, the threshold shift decreased as the stimulus duration increased. This effect was not observed for small contactors.

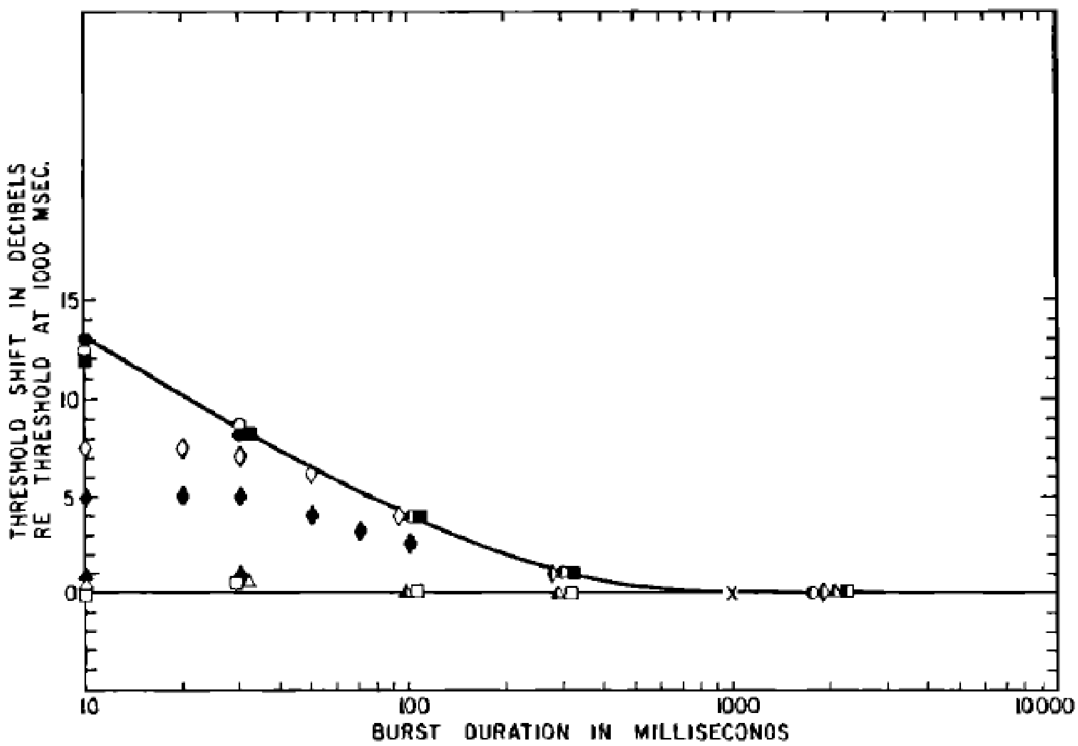


Figure 2.17. The effect of stimulus duration from Verrillo 1965. Open triangles: 0.02 cm^2, 100 Hz; open circles: 2.9 cm^2, 100 Hz; solid triangles: 0.02 cm^2, 250 Hz; solid diamonds: 0.05 cm^2, 250 Hz; open diamonds: 0.08 cm^2, 250 Hz; solid circles: 2.9 cm^2, 250 Hz; open squares: 0.02 cm^2, 500 Hz; solid squares: 2.9 cm^2, 500 Hz.

Verrillo concluded that Zwislocki's theory of temporal summation accurately predicted the threshold shift as a function of pulse repetition rates (frequency), the number of pulses and the burst duration of sinusoidal signal.

The Checkosky and Bolanowski (1992) study also investigated the effect of stimulus duration on the response of the Pacinian corpuscles. The experiments were conducted on Pacinian corpuscles isolated from cat mesentery. The authors concluded that the activity of a single Pacinian corpuscle nerve fibre was insufficient to signal thresholds in the P channel. This finding is in agreement with the conclusion from Zwislocki that temporal summation is not a characteristic of the individual corpuscle, but an ability of the channel.

2.3.9. Effect of skin temperature

Many studies agree that skin temperature affects the thresholds associated with the Pacinian channel (e.g. Bolanowski and Verrillo, 1982; Verrillo and Bolanowski, 1986; Bolanowski *et al.*, 1988).

The Verrillo and Bolanowski study in 1986 investigated the effect of temperature on absolute thresholds for vibration. The thresholds were measured at the thenar eminence and the volar forearm with a 1-mm diameter contactor. Stimuli used in the experiments were sinusoidal vibration at 14 frequencies between 12 and 500 Hz. The tested skin temperatures were between 15 and 40 degrees. The results are given in Figure 2.18. The curves show the thresholds reducing between approximately 15 and 30 degrees. They remained constant between 30 and 40 degrees.

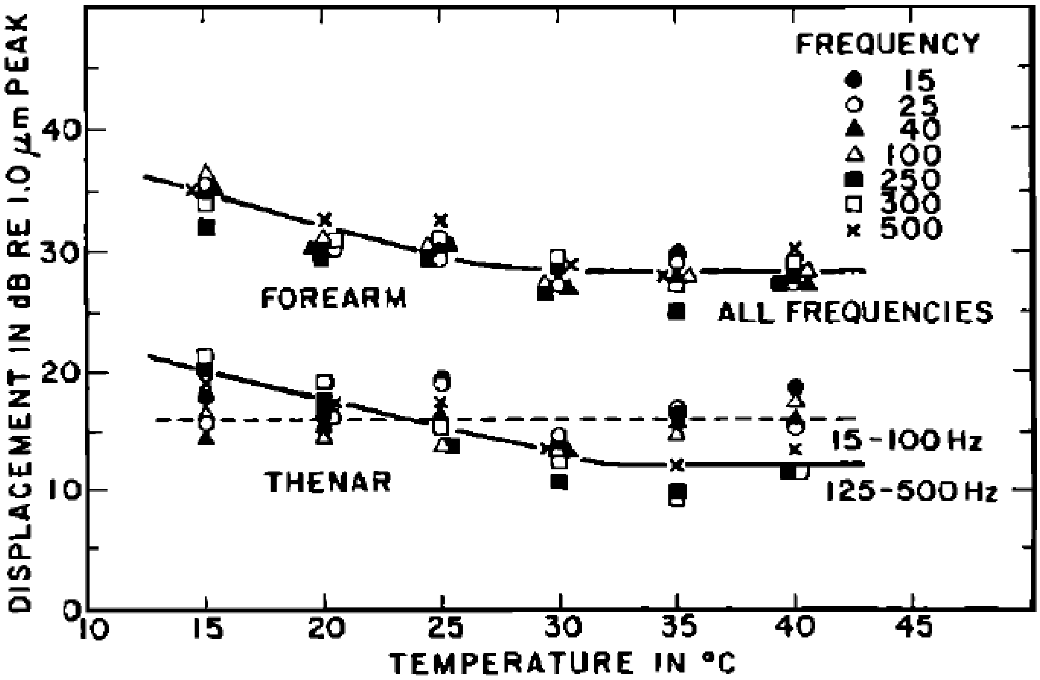


Figure 2.18. The effect of temperature on absolute thresholds from Verrillo and Bolanowski (1986).

Among the factors investigated in the Harada and Griffin (1991) study explained in Sections 2.3.4 and 2.3.5 was the effect of skin temperature. The authors reported that the absolute thresholds were found to be dependent on skin temperature, with the higher frequencies being more affected than the lower frequencies. It was concluded that the physiological characteristics of vibration sensation at low and high frequencies differed significantly.

2.3.10. Effect of masking

Masking is defined as 'a phenomenon in which the perception of a normally detectable stimulus is impeded by a second stimulus' (Griffin, 1996). There are three types of masking. 'Lateral masking' occurs when the masking stimulus is presented at a different location in the same sensory system. Alternatively, if the masking stimulus is presented before the test stimulus 'forward masking', or if it is presented after the test stimulus, 'backward masking' occurs. Masking is only observed when the masker affects the same channel as the test stimulus. Evidence of this is found in Verrillo and Gescheider (1975).

Craig (1976) tested absolute and masked thresholds as a function of contactor area. The test stimulus was input to the left index finger and the masker was input to the little finger of the left hand. It was found that the masker reduced or eliminated the spatial summation effect for high-frequency stimuli. The reduction in the spatial summation appeared to be a direct function of the intensity of the masking stimulus. Also, it was observed that the spatial summation could be attenuated by a masker placed on the contralateral side of the body. This sensitivity to lateral masking indicates that the spatial summation is an ability of the somatosensory channel.

Hamer *et al*. (1982) measured in-channel and cross-channel masking in P and NPI channels, using a 300-ms sinusoidal test stimulus and 700-ms sinusoidal and noise maskers. The stimuli were input to the thenar eminence of the right hand. To selectively excite the two channels two different contactors of 2.9 cm^2 (for the P channel) and 0.005 cm^2 (for the NPI channel) were used. Also, the frequencies of the test stimuli were varied to selectively excite the two channels. The P channel was targeted by the 200-Hz vibration and the NPI by the 20-Hz vibration. The frequencies of the sinusoidal maskers were 70, 200, and 400 Hz. Masker magnitudes varied from -12 dB sensation level to +34 SL. The narrowband-noise maskers were centred at 20 Hz and 200 Hz to target NPI and P channels respectively. The researchers found that the in-channel masking results were 'virtually identical' for the two channels.

Gescheider studied the effects of masking on absolute thresholds in a number of studies with vibration input to the thenar eminence of the hand. The study published in 1982 (Gescheider *et al*., 1982) investigates the threshold shifts due to masking as a function of the intensity of the masker. The masker was narrow-band noise centred at 275 Hz (primarily targeting the P channel), and the stimuli were 15, 50, 80 or 300-Hz sinusoids. The masker intensity was varied from 0 to 52 dB SL.

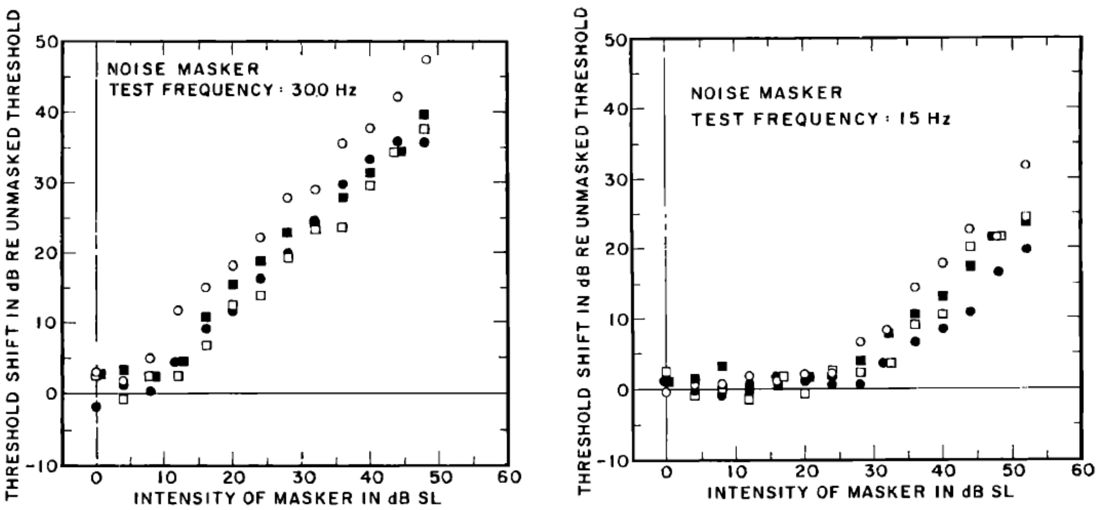


Figure 2.19. The effect of masking from Gescheider et al. (1982). The masker stimulus is narrowband noise centred at 275 Hz. The test stimulus is 300 Hz for the graph on the left, and 15 Hz for the graph on the right. The results from four individual subjects are shown. Each point represents the average of three trials.

The results are shown in Figure 2.19. The thresholds at 300 Hz increase with the increase in the intensity of the masker, as the 275-Hz masker acts on the same channel. The threshold shift is linear with a slope of 1. Thresholds at the 15 Hz test frequency, however, increase only after the masker intensity reaches about 25 dB sensation level. The initial 25 dB increase in the masker, does not affect the NP channel mediating the threshold at 15 Hz.

Another masking study by Gescheider *et al.* (1985) used a 50-ms test stimulus applied 25 ms after the termination of a 700-ms sinusoidal masker. Both the stimulus and the masker were applied to the same site. Frequency conditions for the test and masker vibration in the three masking experiments of the study were:

- Experiment II. 15-Hz masker and 40-Hz test, 40-Hz masker and 15-Hz test
- Experiment III. 15-Hz masker and 63-Hz test, 15-Hz masker and 100-Hz test
- Experiment IV. 15-Hz masker and 300-Hz test, 300-Hz masker and 15-Hz test.

The authors concluded that the findings from these experiments supplied evidence for the three-channel model of vibration perception, including a P channel and two NP channels (NPI and NPII). The results from the 15-Hz masker with 100 or 300 Hz test stimuli experiment indicated that the thresholds at low frequencies were mediated by the NPI system. Results from the experiments with 15-Hz masker and 40, 63 or 100 Hz test stimuli were used in deriving the NPI and NPII frequency characteristics. It was found that NPI frequency characteristic was relatively flat, whereas NPII frequency characteristic decreased at a rate of 5-6 dB per octave to eventually cross the NPI function at about 150 Hz.

Gescheider *et al.* (1989) tested the effects of masking 'stimulus onset asynchrony' and frequency on vibration thresholds (Figure 2.20). The test stimuli were 50 ms in duration and was applied to the thenar eminence of the hand. The masker was a 700-ms suprathreshold stimulus. The stimulus onset asynchrony was modified in order to obtain forward, simultaneous and backward masking conditions. It was found that the threshold shift was greatest when the test stimulus was presented near the onset or offset of the masker stimulus. The authors reported that "for both forward and backward masking, the amount of masking decreased as a function of increasing stimulus onset asynchrony." The authors also reported higher masking effect for noise maskers compared to sinusoidal maskers. The masking effect was identical for the 20 Hz and 250 Hz test stimuli. This finding confirmed the results from earlier studies such as Hamer *et al*. (1982).

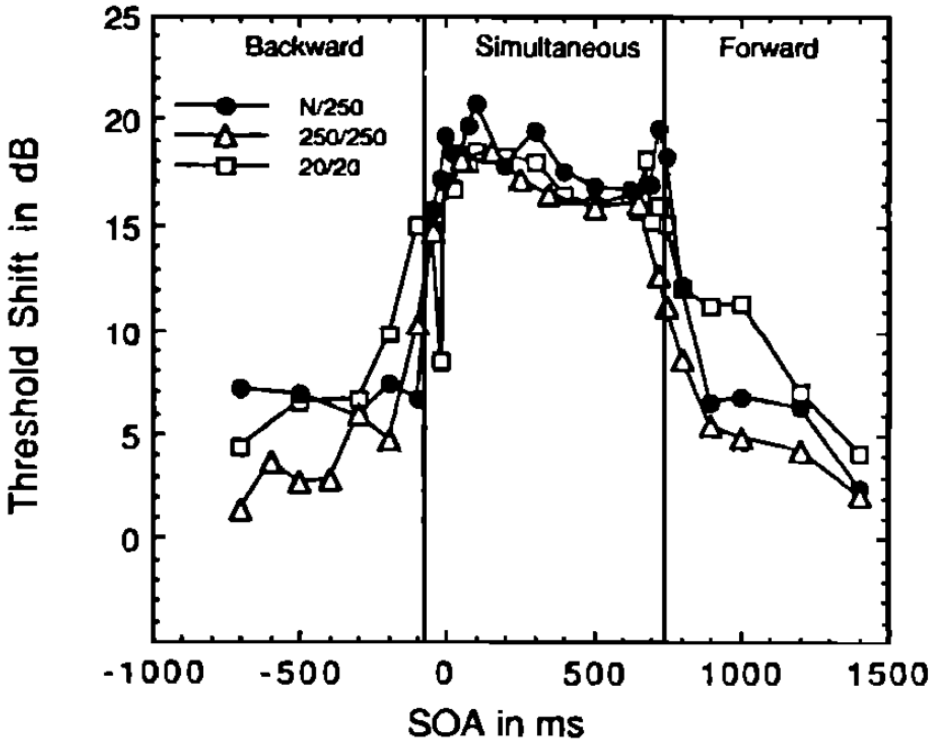


Figure 2.20. The effect of stimulus onset asynchrony from Gescheider *et al*. 1989.

Makous *et al*. (1996) investigated the decay of forward masking effect. The input location was the thenar eminence of the hand. The Pacinian and NP I channels were targeted by masking and test stimuli centred below 27 Hz or at 500 Hz. The delay between the masking and test stimuli was varied from 5 to 995 ms, and the masking stimulus magnitude was varied from 5 to 25 dB sensation level. They found that the masking effect followed an exponential decay with different time constants for each channel (40 ms for the P and about 100 ms for the NPI). The asymptote (residual masking effect) was similar for both channels, being about 1 dB for every 5 dB increase of the masking stimulus level.

2.3.11. Effect of gender

Verrillo (1979a) investigated the effect of gender on absolute thresholds. The thresholds were tested on the thenar eminence of the hand. Twelve male and twelve female subjects took part in the experiment. The mean ages were 23 for men and 24 for women. Thresholds at ten frequencies were tested between (25 and 700 Hz), using a 2.9 cm^2 contactor. No significant differences between the two groups were found. The study also looked at the perception of supra-threshold perception. Six males and six females were tested using magnitude estimation. It was found that women perceived the supra-threshold stimuli more intense than the men.

While other studies also failed to find differences between the genders, including Plumb and Meigs (1961), Steinberg and Graber (1963), Verrillo (1979b), a study by Goff *et al.* (1965), reported that females were more sensitive than males (Figure 2.21).

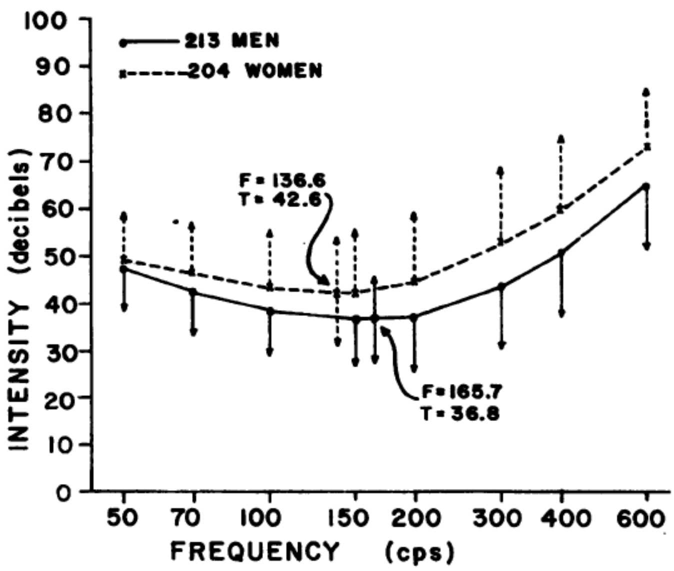


Figure 2.21. Vibration sensitivity curves from Goff et al. 1965.

Parsons and Griffin (1988) found that there were no significant differences between the responses of the male and female subjects for vertical vibration of seated subjects.

A study by Gescheider *et al*. (1984) measured the absolute thresholds for 15 and 250 Hz at the thenar eminence every other day, for a 30 or 40 day period. It was found that while the absolute thresholds for the 15 Hz stimulus did not depend on the menstrual cycle, absolute thresholds for 250 Hz were lowest at the onset of menstruation and highest 12 or 13 days later. The differences were statistically significant.

2.3.12. Effect of age

In 1979, Verrillo published a study which investigated the effect of age on vibrotactile thresholds (Verrillo 1979b). Four groups of six subjects were tested. The groups had mean ages of 10, 21, 50, and 65 years. The oldest age group were free of peripheral neuropathies. A progressive decrease of sensitivity was observed in the P channel mediated thresholds and a gradual steepening of the curve at frequencies below 250 Hz. However, thresholds mediated by the NPI channel was found to have remained unchanged across all four groups of subjects. The author argued that since the NPI channel lacks spatial and temporal summation capability, the reduction of the numbers of mechanoreceptors due to age does not affect the threshold response. The difference observed for the P channel, nevertheless, is likely to be due to the reduction in the numbers of the P corpuscles or due to the changes in their filter characteristics resulting from an overall increase in the number of capsular lamellae (as observed by Cauna, 1965).

Figure 2.22 shows the effect of age on absolute thresholds for the four channels of the glabrous skin.

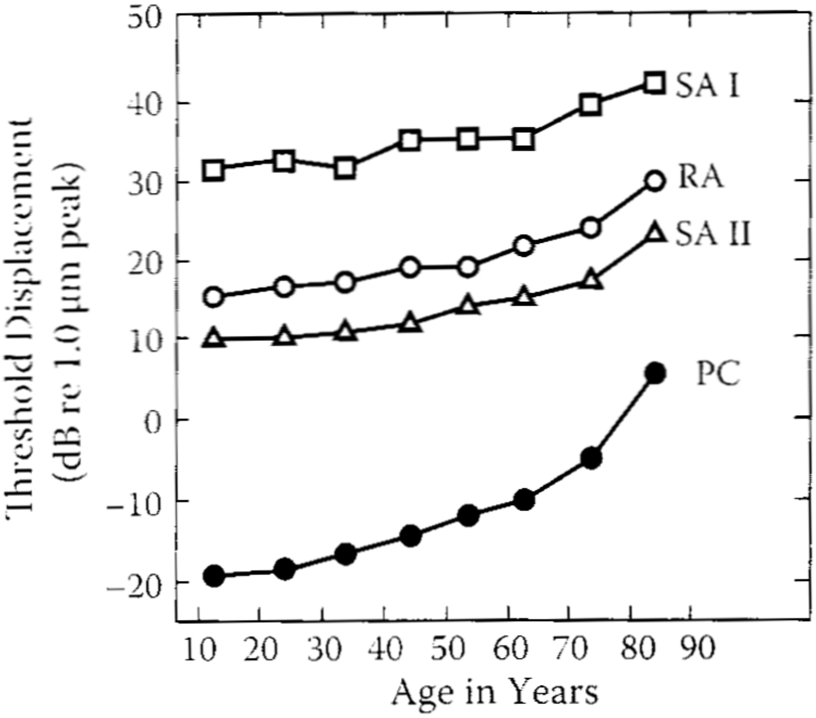


Figure 2.22. Effect of age on the absolute thresholds for four somatosensory channels (from Gescheider et al., 2009).

The findings of this study were repeated in another study by Verrillo (1980). Five groups of subjects with mean ages of 10, 20, 35, 50, and 65 were tested at 11 frequencies. No change was observed at low frequencies (25 and 40 Hz) while sensitivity decreased at high frequencies where the P channel mediates the thresholds.

2.4. DIFFERENCE THRESHOLDS

2.4.1. Introduction

The 'difference threshold', also known as 'just noticeable difference', is the smallest amount of change in a stimulus that can be detected. Although difference thresholds can be defined for all variables in vibration, most of the research in vibration is on intensity (magnitude) difference thresholds, applied vertically to the hand or to the seat. Studies of vibration frequency discrimination by Goff (1967, Figure 2.23) and Rothenberg *et al.* (1977) have found relative difference thresholds ($\Delta f/f$) of about 0.3, with greater thresholds at higher frequencies.

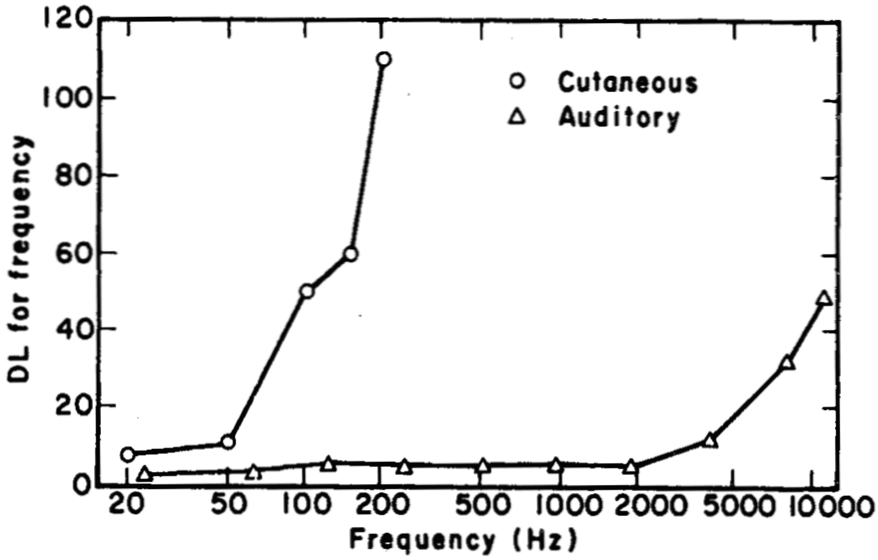


Figure 2.23. Auditory and tactile thresholds for frequency discrimination (from Goff, 1967).

Intensity difference thresholds in vibration can be expressed in absolute values, in units of displacement, velocity, or acceleration. Alternatively, difference thresholds can be expressed using fractions and logarithmic scales. Difference thresholds expressed in fractions of reference intensity are called ‘Weber fractions’, after psychophysicist E.H. Weber. Weber theorised that the fractions would be equal to a constant value, in other words, the smallest amount of detectable change would always be equal to a certain percentage of the stimulus itself. Thus, in the case of magnitude differences, smaller changes would be perceptible when the magnitude of the stimulus is low and bigger changes are needed at higher magnitudes.

Weber’s law is formulated as;

$$\frac{\Delta I}{I} = const. \qquad (2.1)$$

where the I denotes stimulus intensity and ΔI (Figure 2.24) is the absolute difference threshold.

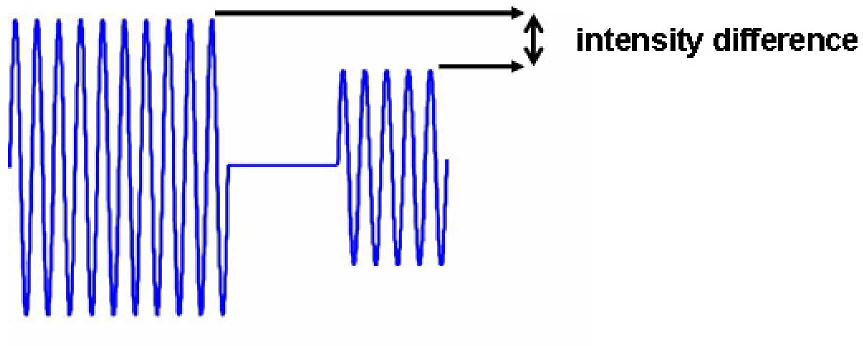


Figure 2.24. Intensity difference (*ΔI*).

2.4.2. Effect of test method

Variants of the method of limits, such as the up-and-down method (sometimes called the staircase method) are commonly used for measuring difference thresholds for vibration intensity. In most variants, the thresholds are obtained by presenting the subject the test and the reference stimuli, which are placed randomly within forced-choice intervals. The difference in intensity (usually stronger), between the test stimulus and the reference stimulus (or stimuli), is increased or decreased depending on the subject's ability to detect it.

In the up-and-down method, the decrease and increase rate of the differences are determined by a tracking procedure. Different tracking procedures estimate the difference threshold at different points. Most common tracking procedures are:

Two-down-one-up: In this tracking method, the amplitude of the test stimulus is decreased after two consecutive correct responses, and it is increased after one incorrect response. This method was used by Bellmann *et al.* (2001) together with the three-interval forced choice method for presentation.

Three-down-one-up: As the name suggests, this method is similar to the two-down-one-up method, but the intensity is modified after three consecutive correct responses instead of two. When used in conjunction with the two-alternative (interval) forced-choice method of presentation, estimates the threshold at 79.4 percent of correct response (For details, see Section 3.4 and Figure 3.7).

Three-down-one-up (not-consecutive): This method is same as the three-down-one-up method, except that the three correct responses needed to reduce difference between the test signal and the reference signal need not be consecutive. When used in conjunction with the two-alternative (interval) forced-choice method of presentation, estimates the threshold at 75 percent of correct response. This method was used in Gescheider *et al.* (1990, 1992, 1994a, 1996a, 1997a).

There are different ways of presenting the test and reference signals to the subjects. Common methods employed in previous studies, as defined in Gescheider *et al.* (1990):

Gated Pedestal: This is the more commonly used method for measuring difference thresholds. In the gated pedestal method, the test and reference stimuli are presented separately, with a pause in between (Figure 2.25).

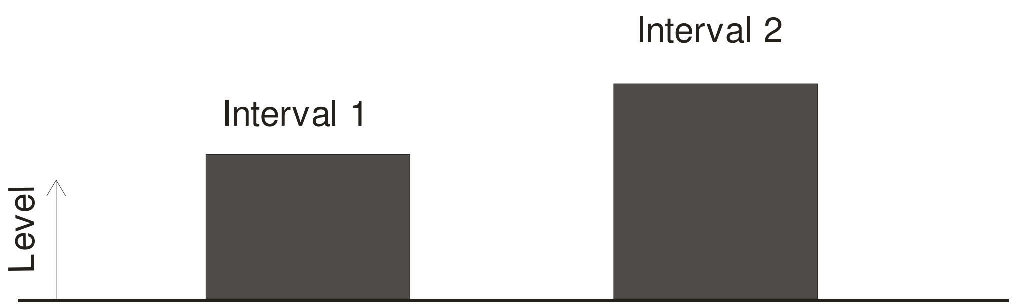


Figure 2.25. Stimuli presented with gated pedestal.

Continuous Pedestal: In the continuous pedestal method, the reference stimulus is presented as a continuous signal. The test stimulus is a period within the continuous pedestal signal when the intensity of the vibration increases above the continuous pedestal level (Figure 2.26).

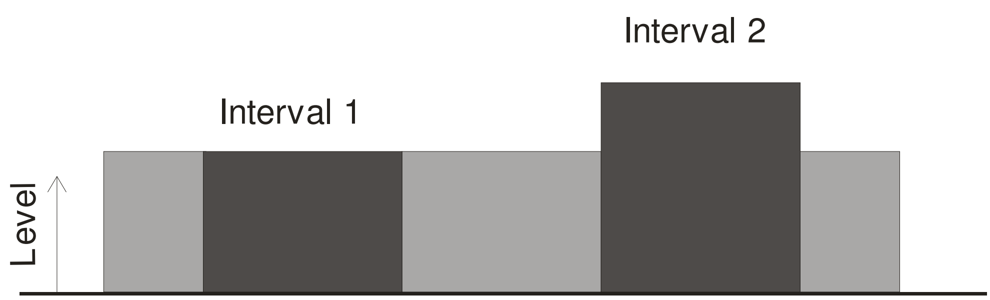


Figure 2.26. Reference and test stimuli presented with continuous pedestal

A study of difference thresholds for whole-body by Matsumoto *et al.* (2002), explained in detail in Section 2.4.3.1, investigated the influence of the order and relative magnitudes of two stimuli used in the two-alternative choice method. They found a difference between the cases when the test stimulus was presented before the reference stimulus and vice versa. They concluded that it the subjects might have judged the second vibration relatively greater than the magnitude of the first vibration. Matsumoto *et al.* found lesser relative difference thresholds in their study than others in literature and contributed these differences mostly to the difference in method, as their method estimated the difference thresholds at 50% correct response point, compared to other researchers who usually estimate the thresholds at higher correct response points (usually above 70%).

An earlier study by Gescheider *et al*. (1990) is also informative on the effect of method on difference thresholds, as its main aim was to compare difference thresholds obtained by three methods. This study is described in detail in Section 2.4.4.2, since it also used different frequencies. The three methods used in this study were the continuous pedestal, gated pedestal, and two-burst continuous pedestal method (which included two separate bursts of pedestals, with only one containing a magnitude increment). They found that the difference thresholds were higher than the thresholds obtained with either the gated or the continuous pedestal methods, especially at low sensation levels. The continuous pedestal relative difference thresholds were also found to be lower than gated-pedestal relative difference thresholds. Gescheider *et al*. suggest that the difference between the two methods could be due to the continuous pedestal's 'priming' of the neural system to detect more effectively.

Other possible explanations offered by the authors for continuous pedestal producing lower relative difference thresholds than gated pedestal was that it required less of the subject's memory or concentration, as the task was less complicated.

Gescheider *et al*. (1996a) study explained in Sections 2.4.4.2 and 2.4.7 also measured the difference thresholds using two different methods. The two methods used in testing were the continuous pedestal method and the gated pedestal method. It was found that the relative difference thresholds decreased substantially with increasing stimulus duration when they were measured by the continuous pedestal method, but no decrease was observed when they were measured by the gated pedestal method.

2.4.3. Effect of frequency

Many studies of difference thresholds, conducted on hand and whole-body, failed to find a dependency of the difference thresholds on stimulus frequency. However, some of these studies employed a narrow range of stimuli or subjects.

2.4.3.1. Whole-body vibration

Pielemeier *et al.* (1997) tested difference thresholds for vertical vibration for subjects on an automobile seat using octave-band noise centred at 4, 8, and 16 Hz frequencies. Three trained subjects took part in the study. Pielemeier *et al*. found relative difference thresholds between 0.08 and 0.18, and concluded that the frequency had no significant effect on the difference thresholds.

Morioka and Griffin (2000) also investigated difference thresholds for vertical seat-input vibration. They used sinusoidal stimuli at two frequencies (5 and 20 Hz) and 12 healthy male subjects seated on a rigid seat. The relative difference thresholds were about 0.1 (10%) and slightly greater at 5 Hz compared to the relative difference thresholds at 20 Hz, but the difference was not statistically significant.

Bellmann (2002) measured whole-body difference thresholds with an adaptive 3-alternative-forced-choice method (Levitt, 1971). Eight subjects (six males and two females) were tested, using vertical sinusoidal stimuli at eight frequencies (10, 12.5, 16, 20, 25, 31.5 40, 50 Hz). The difference thresholds were about 1.5 dB (approximately 0.19) with a standard deviation of 0.5 dB (approximately 0.06). No significant effects of vibration frequency on relative difference thresholds were found (Figure 2.27).

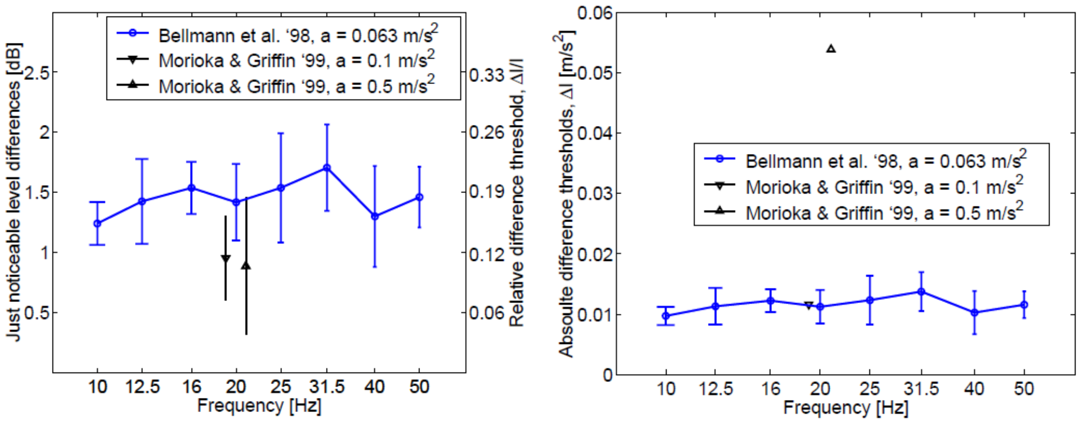


Figure 2.27. Relative (left) and absolute values of difference thresholds, with comparison to other studies. From Bellmann et al. (2000).

Matsumoto *et al.* (2002) measured whole-body vertical vibration difference thresholds at six frequencies (4, 8, 16, 31.5, 63 Hz). This study tested 16 healthy male subjects seated on a flat rigid seat. Matsumoto *et al.* found that subjects tended to be more sensitive to the change in vibration magnitude at 4 Hz than at 16, 31.5, and 63 Hz and less sensitive to the magnitude difference at 31.5 Hz than at 4, 8, and 80 Hz (Figure 2.28).

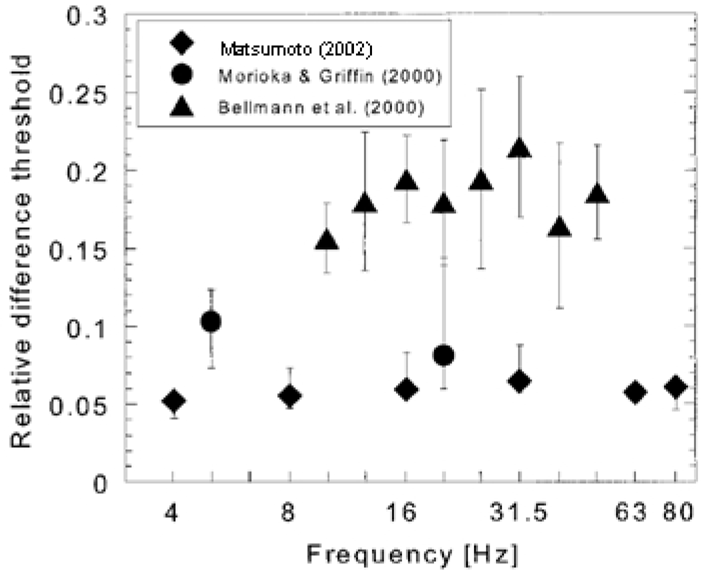


Figure 2.28. Comparison of relative difference thresholds. From Matsumoto et al. (2002).

The Matsumoto *et al.* (2002) study is the only one that found a statistical dependence of relative difference thresholds on the frequency of vibration.

2.4.3.2. Hand-transmitted vibration

Few studies of the difference thresholds for hand-input vibration investigated the effect of frequency.

Gescheider *et al.* (1990) tested difference thresholds at the thenar eminence of the hand, using 25 Hz and 250 Hz sinusoids and narrowband noise. The stimuli were delivered through a 2.9 cm^2 contactor. Six subjects took part in the experiment. The difference thresholds were obtained using three different methods. The authors concluded that regardless of the channel excited, the difference threshold functions were the same. The results are shown in Figure 2.29.

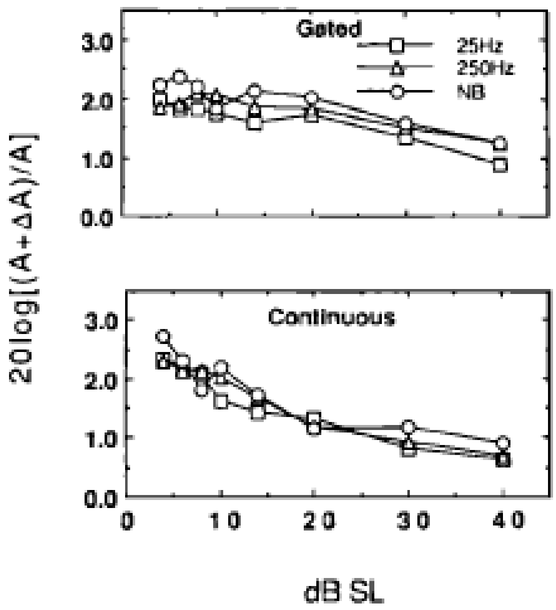


Figure 2.29. Average relative difference thresholds measured by the gated and the continuous pedestal methods plotted as a function of the sensation level at three frequencies. From Gescheider et al. (1990).

Morioka (2001) investigated the effect of frequency on difference thresholds for the hand with a grasping posture. Eight young male subjects took part in the experiment. The difference thresholds were determined at seven frequencies (8, 16, 31.5, 63, 125, 250, and 500 Hz). The study found relative difference thresholds of 0.15-0.18. There were no significant differences between the relative difference thresholds at the tested frequencies (Figure 2.30).

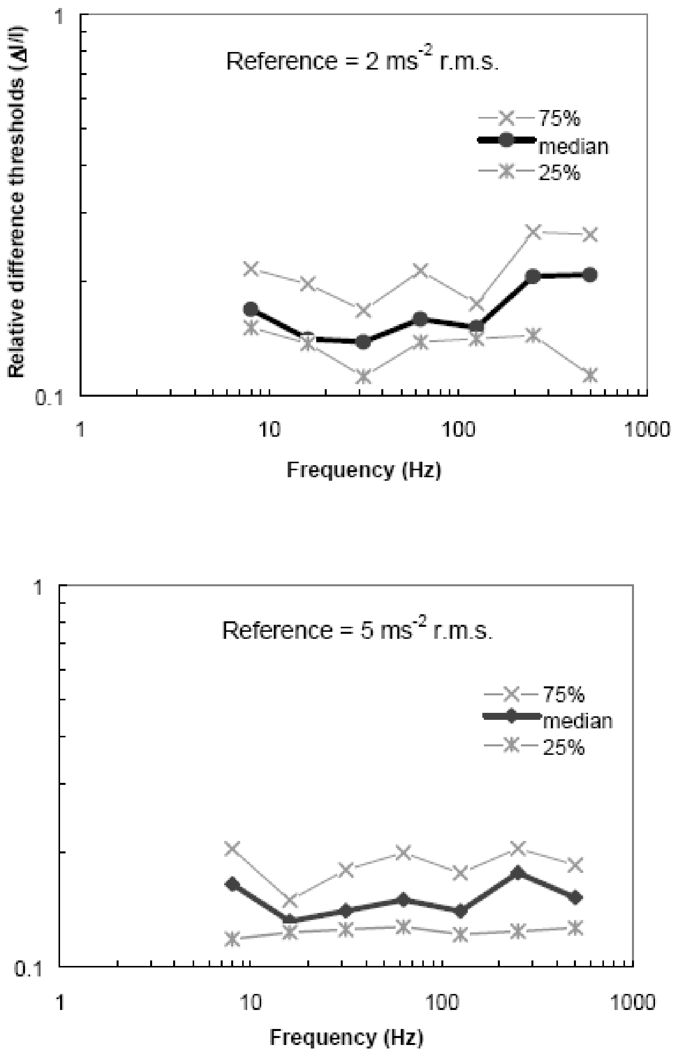


Figure 2.30. The effect of frequency on difference thresholds from Morioka (2001).

The conclusion in this study indicated a possible channel-related effect; Morioka suggested that higher difference thresholds at high frequencies such as 125, 250, and 500 Hz might be due to different mediation characteristics of the Pacinian and the non-Pacinian systems.

2.4.4. Effect of vibration magnitude

Weber's law predicts constant relative difference thresholds for different values of stimulus magnitude. More studies have investigated the effect of magnitude on difference thresholds than the effect of frequency.

2.4.4.1. Whole-body vibration

The Morioka and Griffin (2000) study mentioned in Section 2.4.3.1 measured the difference thresholds at two different magnitudes (0.1 and 0.5 ms^{-2}). Slightly lesser difference thresholds at higher magnitudes (0.11 and 0.12 at 0.1 ms^{-2} compared with 0.08 and 0.10 at 0.5 ms^{-2}) were found. However this difference was not statistically significant and the researchers concluded that the results were consistent with Weber's law (Figure 2.31).

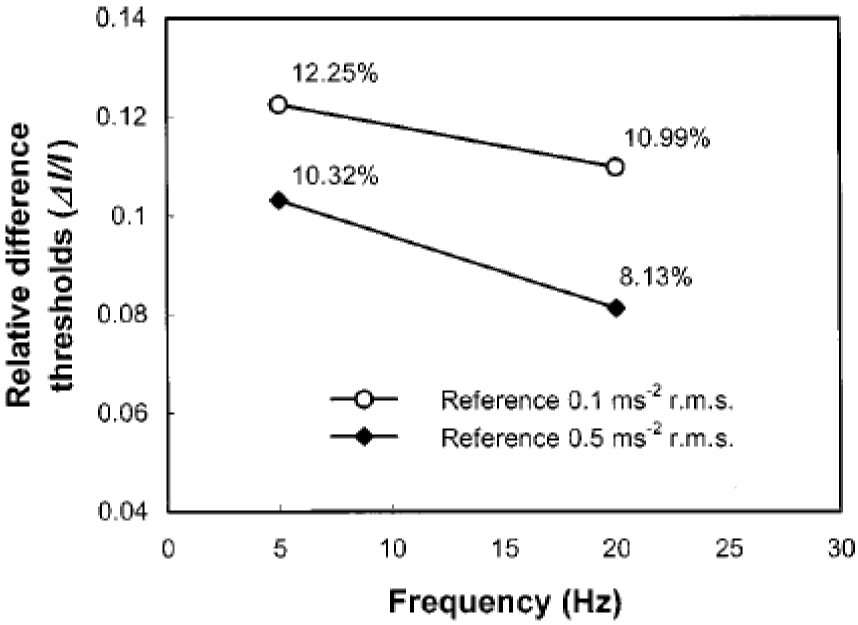


Figure 2.31. Median relative difference thresholds for four vibration stimulus conditions. From Morioka and Griffin (2000).

A study by Mansfield and Griffin (2000) measured the difference threshold for ten male and ten female subjects on automobile seats. Four sets of stimuli reproducing the vertical vibration recorded on the seat of a car were used. Three different magnitudes (0.2, 0.4, and 0.8 ms^{-2} W_b-weighted r.m.s.) were tested with three of the four waveforms. The researches found that difference thresholds for whole-body vibration increased with increasing magnitude of vibration. However, they concluded that the relative difference thresholds were approximately 13%, and independent of both the vibration magnitude and the vibration waveform, and the results were therefore consistent with Weber's law.

2.4.4.2. Hand-transmitted vibration

According to Craig (1972), investigating hand-transmitted vibration, Spector (1954) found that at vibration magnitudes less than 15 dB SL (i.e. 15 dB above the absolute perception threshold), the relative difference thresholds decreased as the vibration magnitude increased. Above 15 dB SL, they were constant, following Weber's law.
Craig (1972) employed 200 ms sinusoidal vibration at 160 Hz, applied to the fingertip through a 6-mm diameter circular contactor to obtain difference thresholds at four vibration magnitudes (14, 21, 28, 35 dB SL). Two young female subjects were trained before

participating in the experiment. The relative difference thresholds were constant at about 0.16 at all four magnitudes (Figure 2.32).

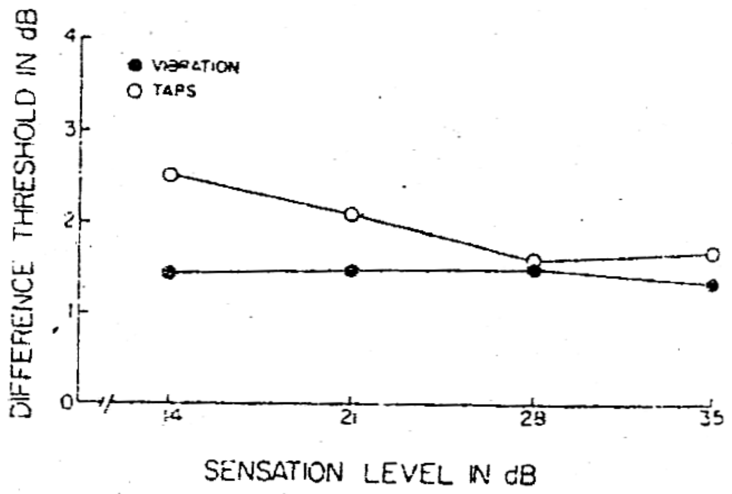


Figure 2.32. Relative difference thresholds from Craig 1972. 'Vibration' refers to 160 Hz sinusoids of 200 ms in duration and 'Taps' refer to a square wave of 2 ms in duration.

In another study also described in the effects of frequency Section (2.4.3.2), Gescheider *et al.* (1990) reported reductions in relative difference thresholds with increasing vibration magnitude (from about 0.26 at 4 dB SL to 0.12 at 40 dB SL). The relative difference thresholds were similar for both frequencies (differing by less than about 0.05). This study is one of the few which mention somatosensory channels in relation to difference thresholds; the researchers concluded that the stimulus-frequency condition did not affect the shape of the difference threshold functions because the process mediating the difference threshold was not channel-specific. Craig (1972) also had a similar finding. Craig reported that when the data are plotted as a function of decibels above either the masked threshold or quiet threshold, a single function was obtained. However, Craig did not attribute this phenomenon to the non-channel-specific nature of difference thresholds.

In a study focusing on the effect of duration on the difference thresholds, Gescheider *et al.* (1996a) found that difference thresholds for 250-Hz sinusoidal vibration, applied to the thenar eminence of the hand through a 3.0 cm^2 contactor, decreased from about 0.26 at 4 dB SL to 0.16 as the vibration magnitude increased to 36 dB SL (Figure 2.33). Similar curves were also obtained in the studies by Gescheider *et al.* 1990 and 1997. The researchers defined these findings as a 'near miss' to Weber's Law – the difference thresholds decreased with increasing vibration magnitude (at 0.015 dB per dB increase in sensation level) over vibration magnitudes from 14 dB SL to 40 dB SL. The expression 'near miss to Weber's Law' is borrowed from research on hearing, Green *et al*. (1979) reports similar findings for hearing.

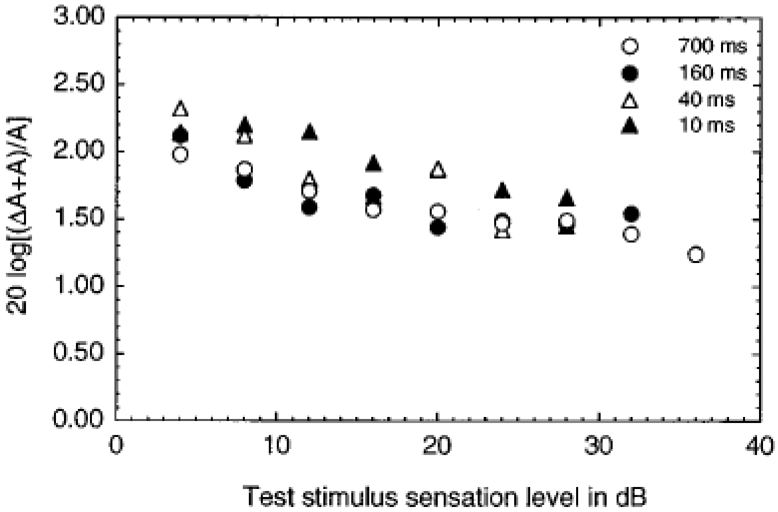


Figure 2.33. Effect of magnitude sensation level on relative difference thresholds from Gescheider et al. (1996a).

The Morioka (2001) study, explained in the section on effects of frequency, reported Weber fractions between 0.16 and 0.19 for two magnitudes of hand-transmitted vibration (2.0 and 5.0 ms^{-2} r.m.s., respectively). As with the frequency of vibration, no significant differences were found between the relative difference thresholds at the two vibration magnitudes at any of the tested frequencies. However, at higher frequencies such as 125, 250 and 500 Hz, the relative difference thresholds were slightly greater at the lower magnitude (mean 0.19) than at the higher magnitude (mean 0.16).

Finally, a study by Gescheider *et al*. (1997a) measured the difference thresholds of four young subjects using 250-Hz bursts of vibration through a 3 cm^2 contactor to the thenar eminence. Contrary to the conclusions in Gescheider *et al*. (1990), in this study a decrease in the relative difference thresholds with increasing Sensation Level was attributed to different discriminative capacities of different somatosensory channels. The authors suggested that the lower difference thresholds above rather than below 25 dB SL could be due to the potentially superior discriminative capacities of the NP channels (especially the NPII channel) relative to those of the P channel.

2.4.5. Effect of masking

There are a plenty of studies available on the effect of masking on absolute thresholds for hand-transmitted vibration (e.g. Gescheider *et al*. 1985, 1989, Makous *et al*. 1995, also

Morioka 2001). However, there are few studies of the effect of masking on difference thresholds, with some suggesting that the difference thresholds can be masked by masking vibration. Craig (1972) and Gescheider *et al*. (1992, 1994a) tested hand-transmitted vibration and found that the relative difference threshold measured at a particular stimulus magnitude was increased by the addition of a masking stimulus.

Craig (1972) used 200-millisecond sinusoidal 160-Hz vibration, applied to the fingertip through a 6-mm diameter circular contactor to obtain masked difference thresholds at three sensation levels (15, 20, 30 dB) in the presence of a broadband noise masker. The difference thresholds decreased as the sensation levels increased, until about 15 dB SL. Craig reported that this behaviour is similar to the behaviour seen in unmasked difference thresholds as observed by Spector (1954), and concluded that the difference threshold curve plotted above the masked threshold would look the same as the difference threshold curve plotted above the unmasked threshold, provided that the two curves are at the same distance from the respective thresholds.

Gescheider *et al*. (1994a) measured masked difference thresholds employing 700 ms sinusoids at 250 Hz**,** to test the hypothesis that predicted that the size of the difference threshold would be independent of the slope of the loudness function, provided the sensation magnitudes of the stimuli are the same (Figure 2.34). The stimuli were applied to the thenar eminence of the hand, through a circular contactor with an area of 2.9 cm^2. This hypothesis was originally derived from similar findings in hearing by Zwislocki and Jordon (1986), Hellmann *et al*. (1987) and Stillmann *et al*. (1993). It was found that the relative difference threshold measured in the presence of a masking stimulus was lower than the difference threshold measured in the absence of a masking stimulus, but the size of the relative difference thresholds was independent of the level of masking noise, provided the subjective magnitudes of the stimuli are equal.

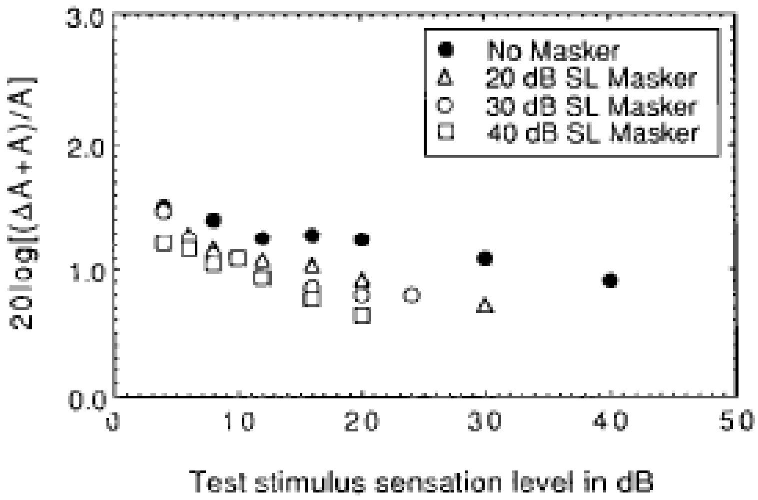


Figure 2.34. Relative difference thresholds expressed in dB as function of the sensation level of the standard stimulus. From Gescheider *et al*. (1994a).

2.4.6. Effect of temperature

Gescheider *et al* (1997a), investigated the effect of temperature on the difference thresholds. This study was previously mentioned in Section 2.4.4.2. Gescheider *et al*. measured the difference thresholds at three different skin temperatures (20, 30, and 40 degrees), using 250 Hz sinusoidal vibration applied to the thenar eminence of the hand. It was found that discrimination capacities were unaffected by surface-skin temperature (Figure 2.35).

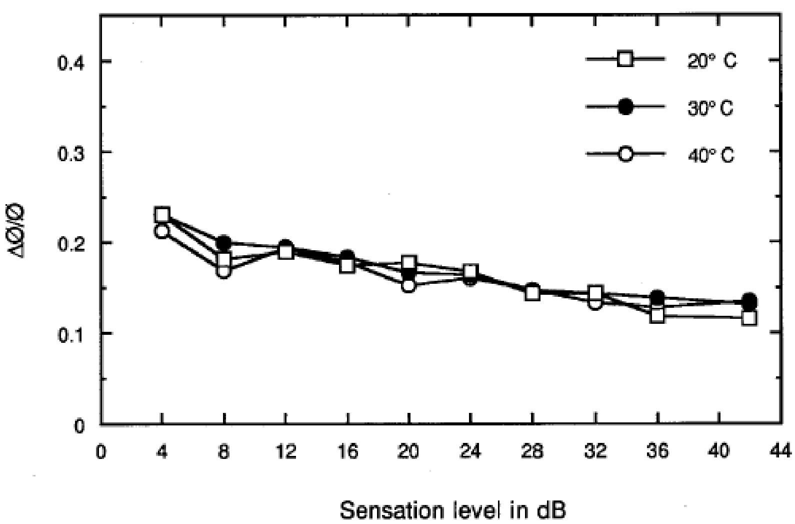


Figure 2.35. Effect of temperature on difference thresholds from Gescheider et al. (1997a).

2.4.7. Effect of stimulus duration

In the study explained in more detail in Section 2.4.3.1, Pielemeier *et al*. (1997) measured the difference thresholds using two stimulus durations of 2 and 4 seconds at 16 Hz. They found that the change in the stimulus duration did not significantly affect the measured difference thresholds.

Gescheider *et al*. (1996a) also investigated the effect of the stimulus duration on difference thresholds. Some details about this study are given in Section 2.4.4.2. Gescheider *et al*. tested four subjects, and used two methods to measure difference thresholds using stimulus durations between 10 to 1000 ms (Figure 2.36).

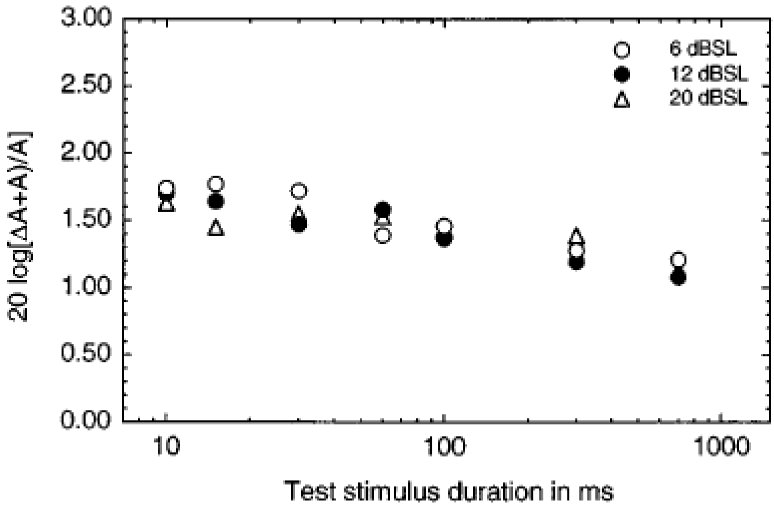


Figure 2.36. Effect of stimulus duration on relative difference thresholds from Gescheider et al. (1996a).

It was found that the difference thresholds were dependent on stimulus duration when the continuous pedestal method (where the ΔI is added to a continuous reference vibration) was used, but they did not show the same dependence when the gated–pedestal method (when reference vibration was separated by a pause from the test vibration) was used. However, at continuous pedestal magnitudes above 40 dB SL, the relative difference thresholds did not show any dependency on increment duration. Similar results were found in another part of the experiment, when the 3 cm^2 contactor was replaced with the 0.01 cm^2 contactor, no dependence of relative difference thresholds were observed.

Both of these findings seem to indicate that the involvement of the NPII channel (in one case activating due to the high sensation level of the stimulus, and in the other case due to the use of small contactor) resulted in different values for relative difference thresholds.

2.4.8. Effect of gender

Mansfield and Griffin (2000), in a study described in the effect of magnitude Section 2.4.4.1 above, measured the difference threshold for ten male and ten female subjects on automobile seats, but found no differences between the relative difference thresholds of the two genders.

2.4.9. Effect of age

There is some indirect evidence from studies indicating that although older subjects have higher absolute thresholds than younger subjects, their relative difference thresholds are not higher than those of the younger subjects.

Gescheider *et al*. (1996b) reported that the relative difference thresholds were unaffected by aging except for stimuli slightly above the detection threshold. For stimuli near the absolute threshold, the relative difference thresholds of older subjects were significantly higher than those of younger subjects.

2.4.10. Effect of direction

All studies reported here investigated the difference thresholds for vibration input perpendicularly to the skin. There are no known studies of the effects of vibration input direction on vibration intensity difference thresholds.

2.4.11. Inter- and intra- subject variability

There are no known dedicated studies of inter- and intra-subject variabilities of vibration difference thresholds.

A number of whole-body vibration studies reported intra-subject variability for difference thresholds. The relative difference threshold data from Morioka and Griffin (2000) had an inter-quartile range of 0.047 (the median relative difference threshold was 0.12) for 5 Hz vibration at 0.1 ms^{-2} r.m.s. reference magnitude, and an inter-quartile range of 0.087 (the median relative difference threshold was 0.08) for 20 Hz vibration at 0.5 ms^{-2} r.m.s reference magnitude. Mansfield and Griffin (2000) study found that the maximum relative difference thresholds were anywhere from 5.8 times to 3.2 times greater than the minimum relative difference thresholds. Bellmann *et al*. (2000) reported a maximum standard deviation of 0.5 dB for difference thresholds. Matsumoto *et al*. (2002) reported lower intra-subject variability than the others. Comparisons of the medians and the inter-subject variabilities from three studies (Matsumoto *et al*., 2002; Bellmann *et al*., 2000; and Morioka and Griffin 2000) are shown in Figure 26, in Section 2.4.3.1.

For hand-transmitted difference thresholds, Gescheider *et al.* (1990) reported standard deviations between 84% of the relative difference thresholds and 95% of the relative difference thresholds. Morioka (1998) reported standard deviations between 14 percent of the difference threshold (125 Hz, 2 ms^{-2} r.m.s. reference) and 53 percent of the difference threshold (63 Hz, 5 ms^{-2} r.m.s. reference).

2.4.12. Effect of learning

How much training the subjects receive before difference threshold measurements varies between studies, but there is only one known study of the effect of learning on vibration difference thresholds. As reported in Gescheider *et al.* (2009), a study by Bolanowski *et al.* (1995), measured the difference thresholds for 23 days and found significant reductions in the difference thresholds, with 20-Hz thresholds dropping from 0.27 to 0.6, and 250-Hz thresholds dropping from 0.23 to 0.10 at the end of the 23-day training (Figure 2.37).

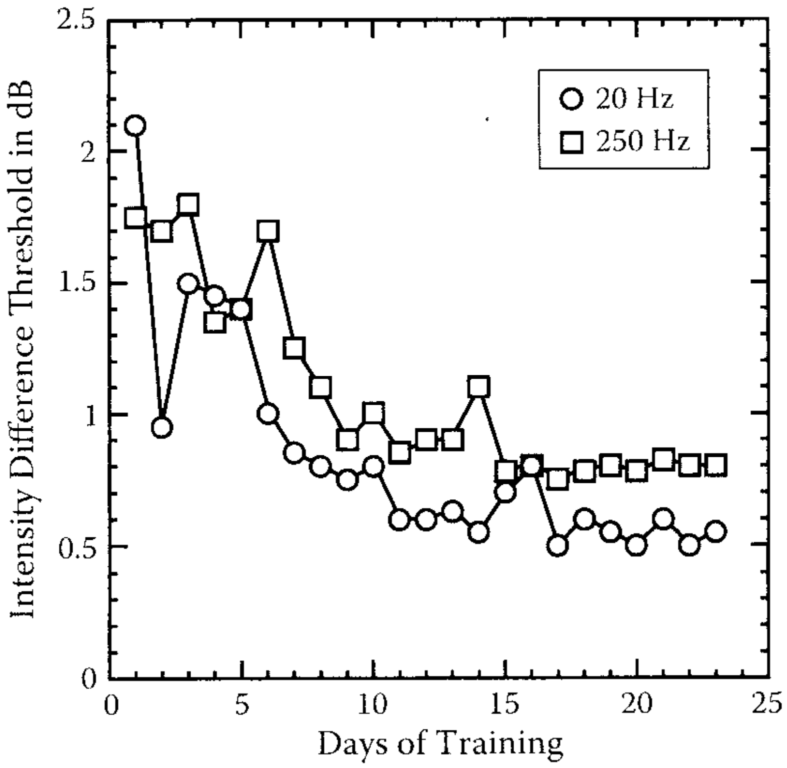


Figure 2.37. Effect of learning on difference thresholds for two frequencies from Gescheider et al. (2009).

Also in another part of this study, some of the subjects were trained to detect the differences with one frequency and it was revealed that the reductions in the thresholds were confined to the frequency in which the subject was trained, providing evidence that the channels were independent even at higher neural levels.

2.5. DIFFERENCE THRESHOLDS OF OTHER SENSORY SYSTEMS

Intensity discrimination ability of the auditory and visual systems have been investigated by researchers in the past. A short overview is given below.

2.5.1. Hearing

Intensity difference thresholds for hearing were obtained using various methods including amplitude modulation, continuous pedestal, and gated pedestal. Differences between the three methods were little. When difference thresholds (*ΔL*) were obtained from sound intensity (*I*) using:

$$\Delta L = 10 \cdot Log_{10}\{(I + \Delta I)/I\} \tag{2.2}$$

the *ΔL* values for wideband noise were about 0.5 to 1 dB (i.e. *ΔI / I* = 0.12 to 0.26) for a reference intensity range of 20 dB SL to 100 dB SL (Miller, 1947, Figure 2.38).

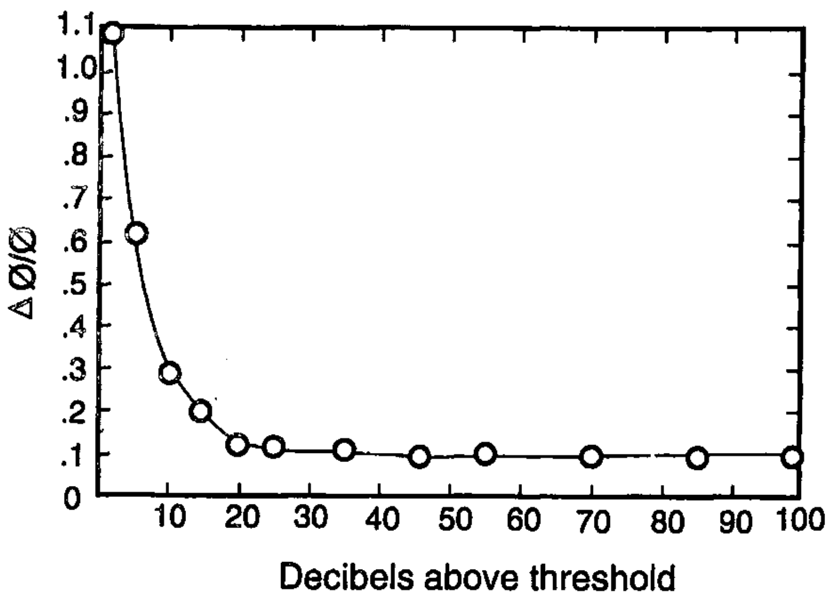


Figure 2.38. Difference thresholds for wideband noise. From Miller (1947).

When sinusoidal stimuli are used, the plot of (*ΔI / I*) gives a slope of about 0.9 instead of 1, which is the slope predicted by Weber's Law. This behaviour has been dubbed the 'near miss' to Weber's Law (McGill and Goldberg, 1968), and it means that the level discrimination improves for sinusoids with increasing reference sound level up to about 100 dB SPL (Goldstein, 2005). Possible models for the near-miss behaviour involving high-frequency non-linearity (Zwicker, 1956 and 1970) and multi-channel processing Florentine and Buus (1981) were suggested.

Green (1988) approximated the near-miss to Weber's Law based on experimental data, for frequencies between 200 and 8000 Hz and for a signal duration of 500 ms:

$$\frac{\Delta P}{P} = \frac{1}{4}\left(\frac{P}{P_0}\right)^{-1/6} \tag{2.3}$$

The *(ΔP/P)* changes from 0.25 near the threshold (0 dB SL) to about 0.05 at 100 dB (Yost *et al.*, 1993). Findings for sinusoidal signals are given in Figure 2.39

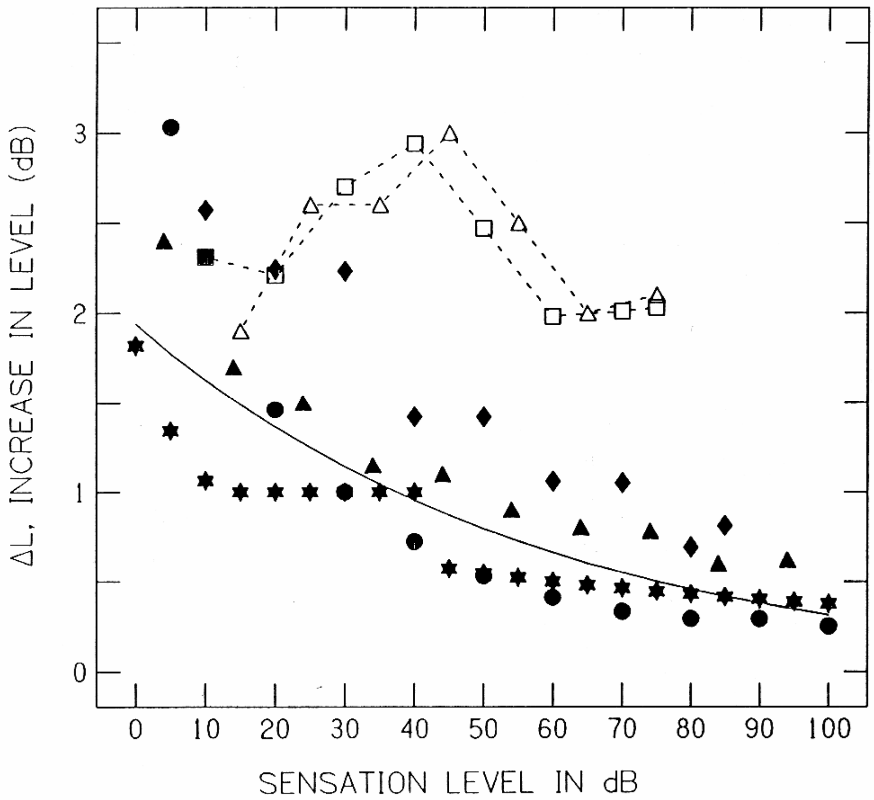


Figure 2.39. Difference thresholds of sinusoidal stimuli. Riesz (1928) - filled circles; Rabinowitz *et al.* (1976) approximation - filled stars; Florentine (1983) 1000 Hz - filled triangles; 14000 Hz - open triangles; Florentine *et al.* (1987) 1000 Hz - filled diamonds, 14000 Hz - open squares; Jestead *et al.* (1977) approximation - solid line. Image from Yost *et al.* (1993).

Garner and Miller (1944), Henning (1970) and Florentine (1986) found that the discriminative ability improved with increasing stimulus duration, up to about 1s.

Shacknow and Raab (1973), Penner *et al*. (1974), found no dependence of discriminative ability on frequency, while Florentine (1983) and Long and Cullen (1985) found higher difference thresholds at higher frequencies.

According to mathematical models and experimental research (Delgutte, 1987, Viemeister, 1988), the firing of a small number of neurons (about 100) is sufficient to account for the observed intensity discrimination capabilities of the auditory system. Carlyon and Moore (1984) and Plack and Carlyon (1995) proposed that since the auditory nerve incorporates about 30000 neurons, which is much more than 100 or so required for the observed performance, the difference thresholds must be limited at a higher level in the nervous system.

2.5.2. Vision

Difference thresholds for vision can be determined in numerous ways. One threshold which may be relevant to detection of motion or vibration is the ability to determine the difference in the distance from the eye of two objects. This task is possible by the cooperation between the two eyes (‘stereopsis’). The visual system is capable of discriminating a difference in distance of 1 mm (Δd) at a reference distance of 1 m (d), which corresponds to a relative difference threshold ($\Delta d/d$) of 0.001 (Blake and Sekuler, 2006).

The concept of visual resolution acuity is defined by the smallest spatial detail that can be resolved. This concept can also be related to difference thresholds, or the perception of motion through vision. Under normal conditions, humans with good vision have a visual acuity of about 1 minute of arc (0.017^{o}). The limit of visual acuity is determined by the spacing of the photoreceptors in the retina of the eye (Wolfe *et al*., 2006).

2.5.3. Olfaction

Gamble (1898) reported relative difference thresholds of 0.25 to 0.35 for odorants.

2.6. CONCLUSIONS

While the body of research on absolute and difference thresholds is quite extensive, it is far from covering all aspects of vibration thresholds.

Since the beginning of psychophysical investigations of somatic senses, progressively more complex models for vibration perception in the glabrous skin of the hand have been developed. One, two, and three channel models were advanced and finally replaced by a four channel model. Investigators also proposed matches of the somatosensory channels with the mechanoreceptors in the skin.

The four identified channels can be grouped according to their adaptation speed, two channels adapt slowly (NPII and NPIII) to a stimulus and the other two adapt rapidly (P and NPI), changing their firing patterns.

According to Gescheider *et al.* (2003), the Pacinian channel differs from the other three channels in a number of ways:

1. It is capable of temporal summation, which operates by neural integration.

2. It is capable of spatial summation.

3. The sensitivity varies more with varying frequency within the P channel than in the NP channels.

4. The masking or adaptation of one channel has no effect on the other channels, although the channels interact in the summation of the perceived magnitudes of stimuli presented to separate channels.

The spatial and temporal summation observed in the P channel is capable of 3 dB reduction in the threshold per doubling of the stimulus duration or area of excitation.

While the frequency-dependent sensitivities of the P and non-P channels are known for hand-input vibration, other input conditions are less well known. Also the influence of factors other than frequency, area, and duration are less well known.

Less is known about difference thresholds compared to absolute thresholds. Some studies exist for whole-body and hand-transmitted difference thresholds, but studies of feet-transmitted difference thresholds are virtually non-existent. While theories for difference perception, usually based on the models for other sensory modalities such as hearing, were developed in the past, mechanisms behind difference perception remain unknown, and there is no accepted conceptual model of difference threshold perception.

While most studies in the literature fail to find a deviation from Weber's law regarding relative difference thresholds for vibration, and some studies conclude that the perception of difference thresholds is a non-channel-specific process, other studies did find deviances from Weber's law and stated that the difference thresholds are channel-specific. Inconsistencies between studies are found in respect to other questions as well.

As such, many questions remain about difference thresholds including:

- Are difference thresholds channel-specific?

- What are their numerical values?
- At which neurological structure are they determined?
- Is Weber's Law valid?
- What is the effect of vibration input location?
- What is the effect of excitation area?
- How large are the intra- and inter-subject variabilities?
- What is the effect of input from other sensory systems?
- What is the effect of masking?

This thesis focuses on the effects of input location, excitation area, vibration frequency, vibration magnitude, and somatosensory channel mediation on vibration intensity difference thresholds. Other relevant factors such as masking, inter- and intra-subject variability of relative difference thresholds and the influence of other sensory systems on vibration intensity relative difference thresholds were investigated as well.

CHAPTER 3: METHOD

3.1. INTRODUCTION

This chapter introduces the apparatus and the methods used in the five experiments reported in this thesis. The experiments used different equipment, contactors and set-ups except for the second and the fourth.

3.2. APPARATUS

Electrodynamic vibrators of different types and sizes were used to produce the motions and piezoelectric accelerometers of various types were used to measure the motions, in the five experiments. The vibration signals were created using *HVLab* software (version 3.81). Details of the equipment are given in the following sub-sections.

3.2.1. Vibrators

In the first experiment, vertical sinusoidal seat-input whole-body vibration was produced by a Derritron VP 180LS electrodynamic vibrator powered by a Derritron 1500-watt amplifier (Figure 3.1).

Figure 3.1. Derritron VP180LS vibrator.

In the second and fourth experiments, the vertical sinusoidal hand-input vibration was produced by a MB Dynamics Model Red electrodynamic vibrator, driven by a MB Dynamics Model SL 500VCF power amplifier. The same model of vibrator and power amplifier were also employed to produce the vertical sinusoidal foot-input vibration in the third experiment (Figure 3.2).

Figure 3.2. MB Dynamics Model Red vibrator.

The vertical sinusoidal vibration input locally to the hand and the forearm in the fifth experiment was produced by an *HVLab* Vibrotactile Perception Meter (VPM) incorporating an electro-dynamic vibrator (Figure 3.3).

Figure 3.3. HVLab Vibrotactile Perception Meter and controller.

3.2.2. Transducers

In all five experiments, the vibrations were monitored using piezo-electric accelerometers. In the first experiment, a PCB model 355BO3 attached to the rigid seat was used. The second, third and fourth experiments employed D.J. Birchall model A/20T piezo-electric accelerometers, attached to the rigid handles in the second and fourth experiments and to the footrest in the third experiment. In the fifth experiment, the piezo-electric accelerometer was integrated into the VPM applicator.

In the first four experiments, signals acquired by the accelerometers passed through Bruel and Kjaer (type 2635) charge amplifiers. The accelerometer in the fifth experiment was connected to the VPM controller.

3.2.3. Signal generation and data acquisition

In all five experiments, the vibration signals were generated and measured using purpose-written scripts in *HVLab* (version 3.81) software. The signals were generated at 5000 samples/second, and were acquired via a Techfilter anti-aliasing filter (1000 Hz low-pass) to a PCL-818 12-bit analogue-to-digital converter.

In the first experiment, the input signals passed through a Kemo low-pass filter (500 Hz) and a Gearing and Watson pre-amplifier (300 W). Input signals in the second, third and fourth experiments also passed through Kemo low-pass filters set at 300 Hz.

Oscilloscopes were used in all five experiments and preliminary tests to monitor the shape of the input and output waveforms to ensure that the distortions of the waveforms were acceptable. Acceleration waveform distortion was measured for the VPM device used in Experiment V, and was found to be between 7.3% and 5.4% for 0.11 to 0.318 ms^{-2} r.m.s. acceleration at 10 Hz.

3.2.4. Auditory masking

White noise was created by calibrated noise generators presented via calibrated headphones in all five experiments to provide auditory masking of any noises the vibrators may produce. The white noise was at 75 dB(A), in Experiments I and III, at 80 dB(A) in Experiment II, and at 65 dB(A) in Experiments IV and V.

3.2.5. Thermocouples

In all experiments except the first, the skin temperature was monitored before the testing started. The measurements were made using thermocouples.

3.2.6. Indicator

An indicator with a red LED, shown in Figure 3.4, was used in all experiments to indicate the measurement intervals to the subjects.

Figure 3.4. The indicator.

3.2.7. Other test conditions

Experiments I, II and III took place in the old laboratory of the Human Factors Research Unit. Experiments IV and V were conducted in the new laboratories. Both laboratories were well-lighted and the subjects were not blindfolded in any of the experiments. In Experiments II and IV, they were instructed to look straight ahead, but the source of vibration (input to the right hand) was within their field of vision (for details of posture, see Section 5.2.2 for Experiment II and Section 7.2.1 for Experiment IV). In Experiment I, the source of vibration was not visible as it was input from the seat, but the resulting motion was visible (see Section 4.2.1). In Experiment III, the vibration was input to the right foot and was not visible to the subject (Section 6.2.2). In Experiment V, the vibration was input through a small contactor obscured by the subject's hand or arm (Section 8.2.2).

The temperature of the laboratory was within normal room temperature range (20-23 degrees Celsius) in all experiments.

Highest background acoustical noise levels, about 60 dBA were observed in Experiment I. In all experiments the headphones produced acoustical noise levels above the noise level at the laboratory, except for the highest magnitudes and frequency condition of the first experiment (i.e. high magnitude condition at 315 Hz, detailed in Section 4.4.2).

3.3. VIBRATION MEASUREMENT

3.3.1. Direction

In all experiments, the vibration was measured in one direction only, the vertical. The vertical direction is in the *z*-axis for whole-body vibration and foot vibration (Figure 3.5) and in the *x*-axis for hand vibration when the hand is held horizontally (Figure 3.6).

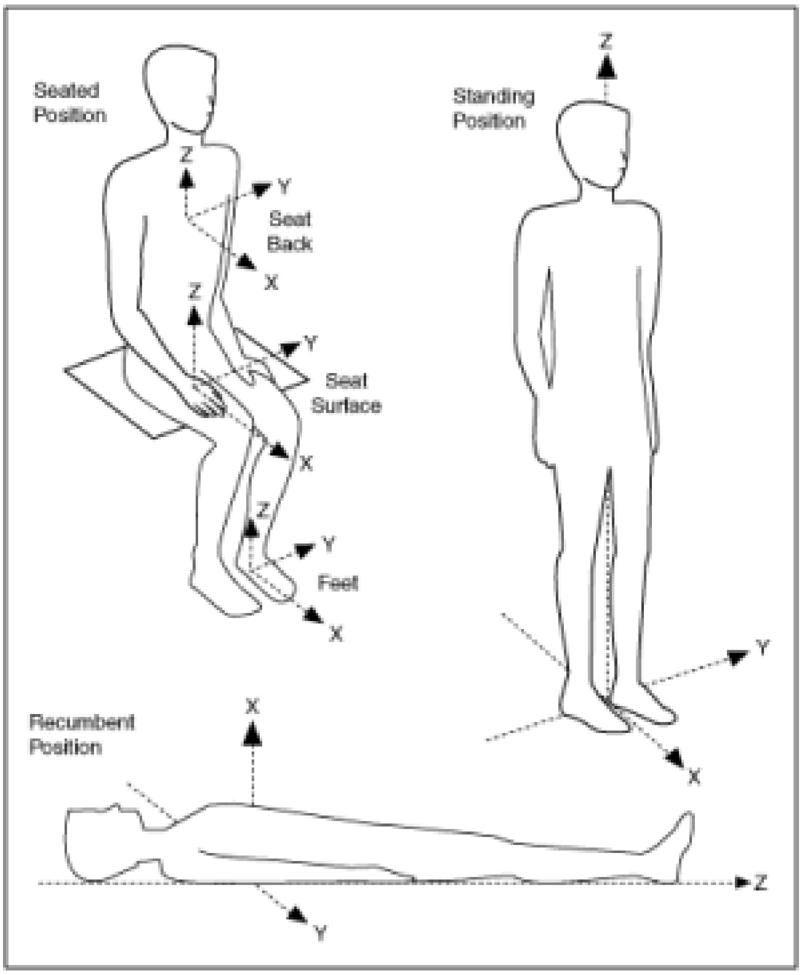


Figure 3.5. Vibration directions as defined by ISO 2631-1:1997 for whole-body vibration, from http://zone.ni.com/.

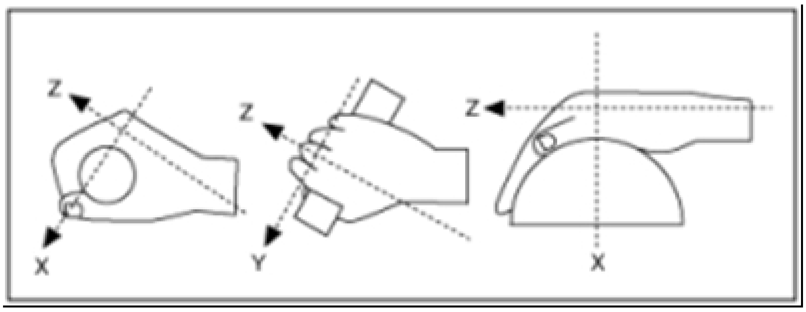


Figure 3.6. Vibration directions as defined by ISO 5349:1986 for hand-transmitted vibration, adapted from http://zone.ni.com/. Coordinates are centred on the head of the third metacarpal. In the experiments of this study, the grasping posture was similar to the one at the right, so that the x-axis pointed straight down (e.g. Figure 5.1).

3.3.2. Magnitude

The vibration magnitude was measured with accelerometers and is mainly presented in acceleration units in this thesis. While some literature, especially on absolute thresholds, discusses the magnitudes of vibration in displacement units, acceleration measurement is also common. It is possible to convert the data in acceleration units into displacement or velocity units, when needed.

3.3.3. Calibration

Rion (type VE-10) and Bruel and Kjaer (type 4294) calibrators were used to calibrate the accelerometers before each experiment. Both of these calibrators produce vibration with a constant magnitude (10 ms^{-2} r.m.s.) and a constant frequency (159.2 Hz).

3.3.4. Background noise

Background vibration (i.e. noise) was measured before the experiments for all vibrators. The main source of the noise was electrical, with a frequency of 50 Hz, and was not perceptible in any of the five experiments. Table 3.1 gives the background vibration levels for the five experiments.

Table 3.1. Background vibration levels.

Experiment	Vibrator	Typical background vibration (ms^{-2} r.m.s.)
I	Derritron VP 180LS	0.012
II	MB Dynamics Model Red	0.011
III	MB Dynamics Model Red	0.009
IV	MB Dynamics Model Red	0.011
V	HVLab VPM	0.020

3.3.5. Safety and ethics

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.

3.3.6. Instructions and questionnaires

Subjects were given written instructions in all experiments. The instructions are reproduced in Appendix A. Personal data was collected on all the subjects who were pre-screened using health questionnaires in all experiments. The questionnaires are given in Appendix D.

3.4. PSYCHOPHYSICAL METHODS

3.4.1. Up-down-transformed-response

A variant of the up-down-transformed-response (UDTR) method, first described by Wetherill and Levitt in 1965, was used to determine the thresholds in all five experiments. In this method, the magnitude of the test stimulus is modified by fixed step sizes depending on the responses of the subject.

All five experiments reported in this thesis used the two-interval-forced choice method, in which the test stimulus is presented in one of two intervals. The intervals were separated by a 1-second pause. Which of the two intervals contained the test stimulus was determined randomly in each trial. The subjects' task was to determine which of the two intervals contained the test stimulus.

In all five experiments, responses of the subjects were tracked using the three-down-one-up rule (i.e. for every three consecutive correct responses, the magnitude of the test stimulus was reduced by one step, and for each incorrect response, it was increased by one step). Figure 3.7 shows sample response data.

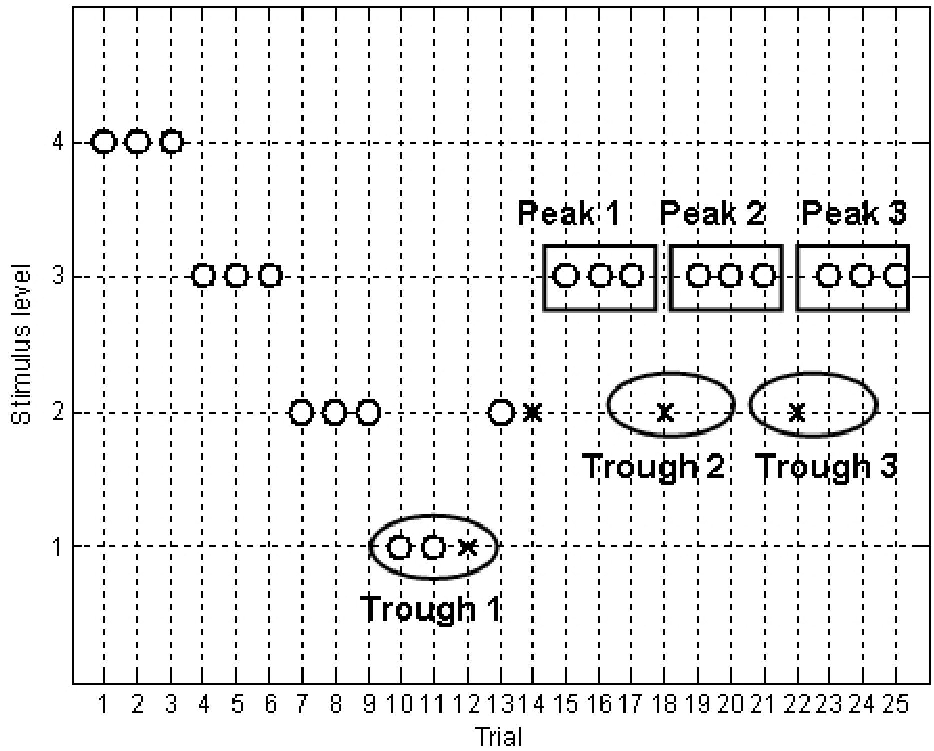


Figure 3.7. Three-down-one-up procedure. **o** indicates a correct response and **x** an incorrect response. Trials 12, 17, 18, 21, 22 and 25 are the reversal points, where 12, 18 and 22 are the troughs and 17, 21 and 25 are the peaks. The threshold is estimated by averaging the values at 18, 21, 22 and 25.

Points on the response data where the upward or downward trend changes direction are called the reversal points. Reversal points where the trend turns upwards are called the troughs and points where the trend turns downwards are called the peaks. In all experiments, the threshold measurements were terminated after six reversal points were obtained. The thresholds were then estimated by averaging the values at the final four reversals points. When six reversal points were not obtained due to subject, operator or equipment errors, the thresholds were obtained by averaging the third and fourth reversal points: the first two reversal points were always ignored. The method used in the experiments estimate the thresholds at 79.4 percent of correct response.

The details of the application of the method are given in the following sections.

3.4.2. Starting levels

In the first two experiments, threshold measurements started at magnitudes near the estimated median threshold. In the third, fourth and fifth experiments, the threshold measurements started at higher magnitudes so that the subjects would respond correctly in the initial trial.

3.4.3. Order of measurements

In all experiments, the difference threshold tests were balanced using a Latin square test order. This was done to prevent order effects.

3.5. DATA ANALYSIS

3.5.1. Data analysis software

Mathworks MATLAB software (version 7.0.4.365.R14) with Statistics Toolbox was used to analyse the results. Custom written scripts were used to calculate the thresholds and perform the statistical tests. Sample scripts used for data analysis are included in Appendix C.

SPSS Inc. SPSS version 16.0 software was also employed in statistical analysis of the location of sensation data obtained in the first and the third experiments.

3.5.2. Statistical methods

Non-parametric tests were employed in the statistical analysis. Friedman test for *k*-related samples and the Wilcoxon matched-pairs signed ranks test for two-related samples were used in all experiments. Cochran's Q and McNemar tests were employed for the statistical analysis of the location of perception data obtained in the first and the third experiments.

CHAPTER 4: DIFFERENCE THRESHOLDS OF WHOLE-BODY VIBRATION

4.1. INTRODUCTION

The first experiment in this thesis investigated vertical whole-body vibration relative intensity difference thresholds. While a number of studies failed to find a dependence of relative difference thresholds on vibration magnitude or frequency, Matsumoto *et al.* (2002) reported a frequency-dependence in the relative difference thresholds for vertical whole-body vibration from a seat (Section 2.4.3.1). No previous experiment has investigated whole-body vibration with a wide frequency range and multiple vibration magnitudes so as to obtain information on the frequency-dependence and magnitude-dependence of relative difference thresholds.

When seeking to reduce sensations caused by whole-body vibration it is useful to know how much the magnitude of vibration must be decreased for the reduction to be noticeable. Any single change less than the difference threshold will not be noticed. People are most sensitive to vibration acceleration at low frequencies (e.g. less than about 20 Hz) and in many environments low frequency vibration is the dominant source of discomfort. Although high frequency vibration may be attenuated by soft seating, it is often above the absolute threshold for perception. In some situations (e.g. vibration from machinery in a building, engine vibration in some cars, and engine vibration on motorbikes) a reduction of high frequency vibration as well as a reduction of low frequency vibration can be desirable. In other situations, a sufficient increase in the magnitude of high frequency vibration may communicate useful information, such as a fault condition. It is therefore of practical interest to know the difference thresholds for vibration over a wide range of frequencies and magnitudes.

Vibrotactile thresholds on the glabrous skin of the hand are mediated by one or more of four psychophysical channels (Bolanowski *et al.*, 1988; Gescheider *et al.*, 2001). The Pacinian (P) channel, mediated by Pacinian corpuscles, often has the lowest threshold at high frequencies (e.g., greater than 40 Hz) and exhibits both spatial and temporal summation: the thresholds reduce as either the area of excitation or the duration of vibration increase. Of the three non-Pacinian channels, NPI often determines thresholds at low frequencies (e.g., less than 40 Hz) and has the Meissner corpuscle as the mechanoreceptor. The NPII channel responds to vibration in the same frequency range as the Pacinian channel but is directionally sensitive to the stretching of the skin and has a higher threshold than the Pacinian channel (Bolanowski *et al*., 1988). The NPIII channel may have a lower threshold than other channels in the range 0.4 to 4 Hz. Other sensory channels can be responsible for absolute thresholds for the perception of vibration in other areas of the body. Assuming more than one channel can be responsible for difference thresholds, the different characteristics of the different channels (e.g., Pacinian and non-Pacinian systems) may result in variations in difference thresholds as the frequency or magnitude of vibration, or the area of excitation on the body, changes. More details on the somatosensory channels can be found in Sections 2.2 and 2.3.

Only a few studies have measured the difference thresholds for the perception of whole-body vibration (Bellmann *et al*., 2000; Mansfield and Griffin, 2000; Matsumoto *et al*., 2002; Morioka and Griffin, 2000). The median relative difference thresholds reported from these studies range from about 0.05 (Matsumoto *et al*., 2002) to 0.25 (Bellmann *et al*., 2000).

Weber's Law (i.e., the relative difference threshold is independent of vibration magnitude) has been tested in some studies. Using vibration recorded in cars, Mansfield and Griffin (2000) found that relative difference thresholds did not vary with changes in vibration magnitude. With sinusoidal vibration at 5 and 20 Hz, Morioka and Griffin (2000) found lower relative difference thresholds at a higher magnitude (0.5 ms^{-2} r.m.s.) than at a lower magnitude (0.1 ms^{-2} r.m.s.), although the difference was not statistically significant.

The effect of vibration frequency on the relative difference threshold has also been investigated. Morioka and Griffin (2000) at 5 and 20 Hz, and Bellmann *et al*. (2000) at 10 to 50 Hz, found no significant effects of vibration frequency on relative difference thresholds. However, Matsumoto *et al*. (2002) reported 'subjects tended to be more sensitive to the change in vibration magnitude at 4 Hz than at 16, 31.5, and 63 Hz and less sensitive to the magnitude difference at 31.5 Hz than at 4, 8 and 80 Hz'.

Different frequencies of vertical whole-body vibration are felt in different parts of the body (Whitham and Griffin, 1978). Vertical vibration of seated persons at low frequencies (e.g., less than 16 Hz) is felt mostly in the lower body. At intermediate frequencies (e.g., 16 to 31.5 Hz), the sensations can be greatest at the head. At higher frequencies, the sensations are localised around the input to the body adjacent to the surface of the seat. So, with vibration of different frequencies being detected in different locations, it would not be surprising if relative difference thresholds for whole-body vertical vibration vary with the frequency of vibration.

This study was designed to determine difference thresholds for vertical vibration of seated subjects, examining the effect of the frequency and magnitude of vibration. It was hypothesised that difference thresholds would depend on both vibration frequency and vibration magnitude.

4.2. EXPERIMENTAL METHOD

4.2.1. Apparatus

Vertical whole-body vibration was produced by a VP 180LS electrodynamic vibrator powered by a 1500 watt amplifier (Derritron, Hastings, UK) and monitored using a model 355BO3 piezo-electric accelerometer (PCB Piezotronics, Depew, New York, USA). The vibration signals were generated and measured using a specially written programme (HVLab version 3.81, HFRU, ISVR, University of Southampton, UK). Signals from a personal computer were generated at 5000 samples/second and passed through a 500-Hz low-pass filter (Kemo Inc, Greenville, USA) and a 300-watt pre-amplifier (Gearing and Watson Electronics, Hailsham, UK).

The set up is shown in Figure 4.1.

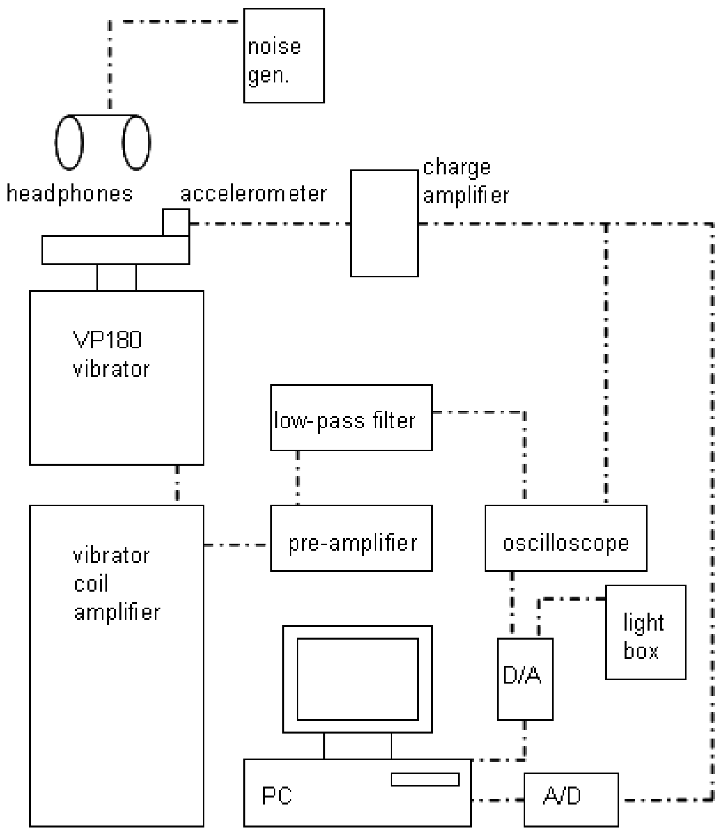


Figure 4.1. Schematic diagram of the set-up.

Figure 4.2. The rigid seat mounted on the vibrator.

A contoured rigid wooden seat (250 x 180 x 70 mm) attached to the vibrator table was large enough to provide contact with the ischial tuberosities but not the thighs (Figure 4.2). Subjects sat in a comfortable upright posture with their hands and feet supported by stationary handles and footrests (Figure 4.3).

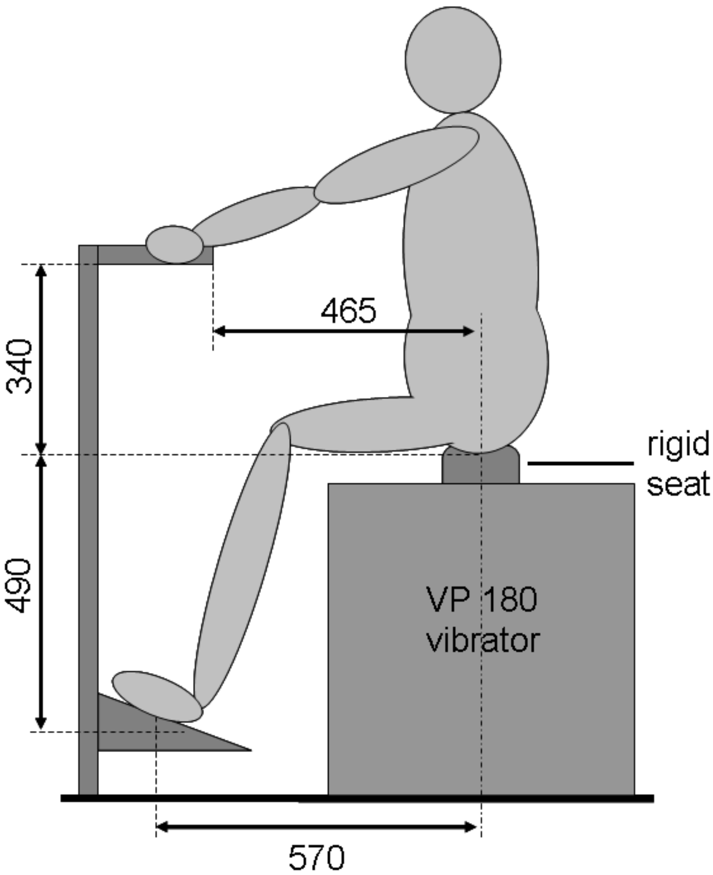


Figure 4.3. Schematic diagram showing the subject posture.

Auditory masking, white noise at 75 dB(A), was provided to the subjects using a pair of headphones.

Written instructions given to the subjects can be found in Appendix A.

4.2.2. Stimuli

Difference thresholds were determined for sinusoidal vertical vibration at octave intervals in the frequency range 2.5 to 315 Hz (i.e., at 2.5, 5, 10, 20, 40, 80, 160, and 315 Hz), and for three vibration magnitudes (referred to as 'low', 'middle', and 'high'). For the low, middle, and high magnitudes, the vibration acceleration was 0.05, 0.2, and 0.8 ms^{-2} r.m.s., respectively, from 2.5 to 40 Hz and the vibration acceleration increased in proportion to frequency at frequencies greater than 40 Hz (so the vibration velocity was 0.0002, 0.0008, and 0.0032 ms^{-1} r.m.s., respectively, from 40 to 315 Hz). The magnitudes were chosen to provide similar sensation levels (i.e. excitation in terms of decibels above the absolute threshold) at all frequencies.

The sinusoidal vibration stimuli were of 2 seconds duration, including 0.5-second rise and decay times – stimulus duration is reported to affect difference thresholds only at durations less than 700 ms for 250 Hz vibration (Gescheider *et al.*, 1996a).

4.2.3. Procedure

Difference thresholds were determined using a two-interval forced-choice (2IFC) method. Subjects were presented with two motions, a reference and a test motion in random order, and were asked to identify the stronger motion (the 'test motion' was always greater than the 'reference motion'). The two intervals were separated by a 1-second pause.

The up-down-transformed-response (UDTR) method, a variant of the method of limits, was used to determine difference thresholds (Wetherill and Levitt, 1965). The three-down one-up rule was used to track the responses of the subjects: when three consecutive correct responses were given, the magnitude of the test stimulus was lowered by one step (0.25 dB), and when an incorrect response was given, the magnitude of the test stimulus was increased by one step.

With the highest magnitude of vibration at the highest frequency (i.e., 6.3 ms^{-2} r.m.s. at 315 Hz), sound produced by vibration of the seat was audible (at about 65 dBA). The 75 dBA white noise masker from the headphones was not sufficient to mask the 315-Hz tone produced by the vibrator. To investigate the effect of this sound, difference thresholds for the high magnitude at 315 Hz were also determined with the seat detached from the vibrator so that it was supported without vibration at the same location. In this condition, subjects provided difference thresholds in the same way as when exposed to vibration, with auditory masking.

After the difference thresholds measurements, the subjects were presented with the reference vibrations once more, in order to determine the locations where they experienced the motion. They reported the locations using a body map (Figure 4.4).

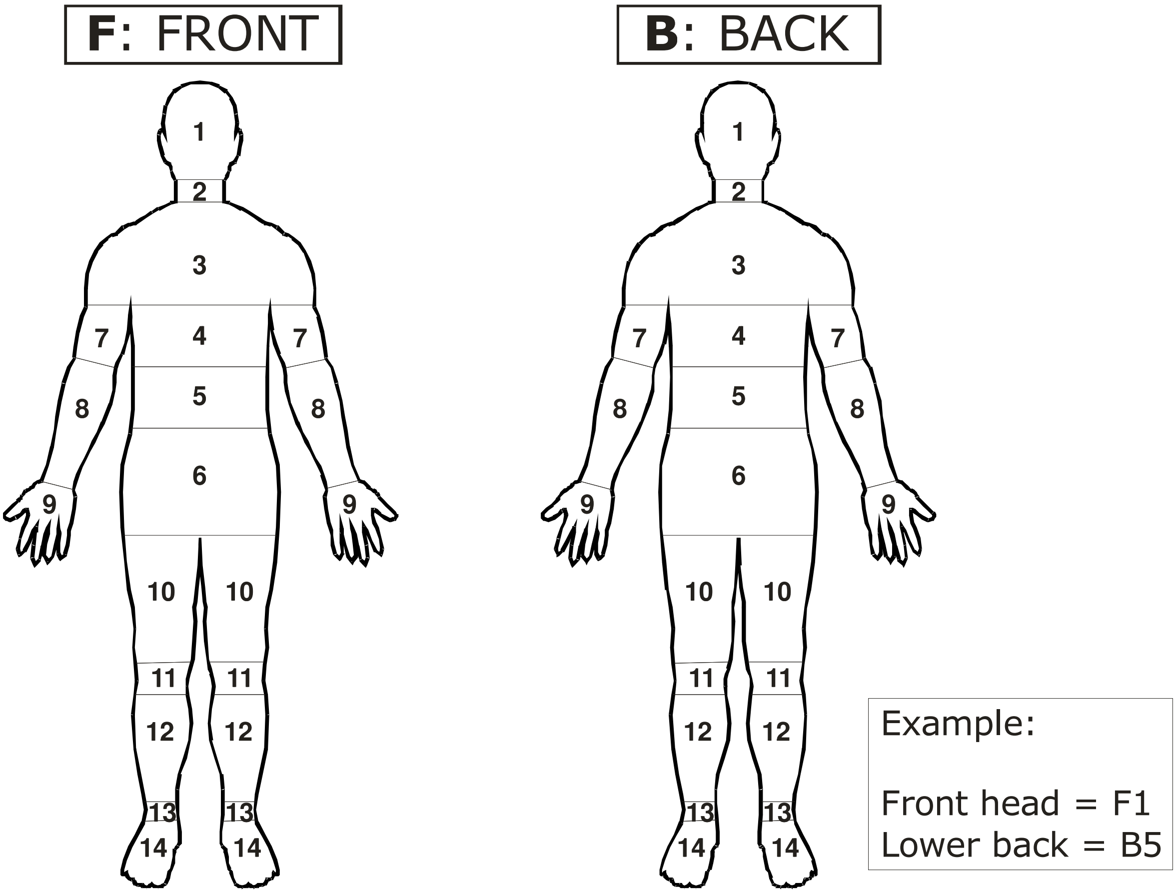


Figure 4.4. Body map used in the location of sensation tests.

4.2.4. Sessions and subjects

The experiment was conducted in three sessions of approximately one hour with subjects attending on three different days. In each session, difference thresholds were determined for all eight frequencies at one magnitude of vibration. Within a session, subjects had a unique balanced exposure pattern, alternating one of the four higher frequencies with one of the four lower frequencies.

Twelve young and healthy males participated in the study. They had a median (range) stature of 180 cm (169 to 194 cm), weight of 71 kg (57 to 92 kg), and age of 25 years (23 to 29 years). The experiment was approved by the Human Experimentation, Safety and

Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

4.2.5. Evaluation of difference thresholds

Absolute difference thresholds were determined from the difference between the magnitude of the reference stimulus and the magnitude of the test stimulus at the peaks and troughs in subject responses (i.e., the reversal points):

$$\text{absolute difference threshold} = \frac{\sum_{i=1}^{N=4}(M_i - R_i)}{N} \tag{4.1}$$

where N is the number of reversals and M_i and R_i are, respectively, the measured accelerations of the test and reference stimuli at the reversals. The experiment was terminated after six reversals, with the first two reversals excluded from the calculation of the difference threshold, so N = 4.

To determine a relative difference threshold (i.e., the relative difference threshold), the absolute difference threshold for that stimulus was divided by the acceleration magnitude of the reference vibration, R_i:

$$\text{relative difference threshold} = \sum_{i=1}^{N=4}\left(\frac{M_i - R_i}{R_i}\right)\cdot\frac{1}{N}\cdot 100 \tag{4.2}$$

In cases where six reversals could not be obtained due to operator or subject errors (seven measurements out of 300), the absolute and relative difference thresholds were calculated using the two reversals after the first two were discarded.

4.3. RESULTS

The median relative difference thresholds are presented in Figure 4.5. They varied from about 0.09 at 2.5 Hz (at the high magnitude) to 0.20 at 315 Hz (at the low magnitude).

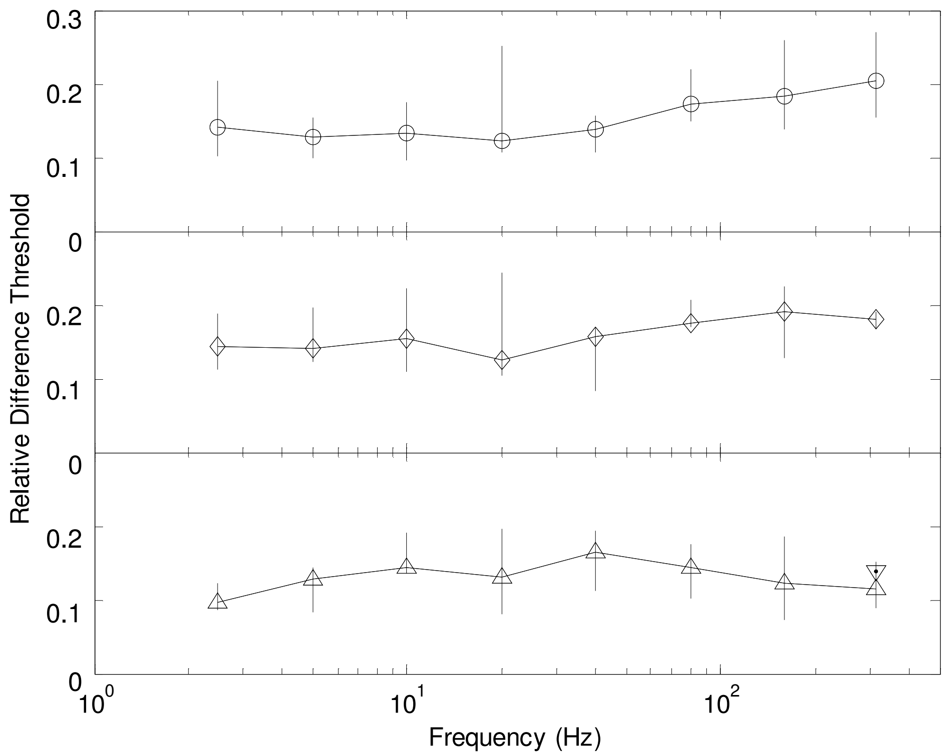


Figure 4.5. Median relative difference thresholds (relative difference thresholds) and inter-quartile ranges: ○ low magnitude, ◊ medium magnitude, ∆ high magnitude; ∇ hearing 315-Hz stimulus at highest magnitude.

4.3.1. Effect of vibration frequency

With the lowest magnitude of vibration, there was a marginally non-significant variation in the relative difference threshold with vibration frequency (*p* = 0.078; Friedman; Figure 4.5). The lower frequencies (2.5 to 40 Hz) had lower median relative difference thresholds, while the higher frequencies (80, 260 and 315 Hz) had higher median relative difference thresholds. Relative difference thresholds at 5 and 40 Hz were significantly lower than those at 80, 160 and 315 Hz (*p* < 0.013; Wilcoxon matched-pairs signed ranks test). The difference threshold was significantly lower at 2.5 Hz than at 315 Hz (*p* < 0.003, Wilcoxon).

There was no indication of an effect of vibration frequency on relative difference thresholds with the middle magnitude of vibration (p = 0.200; Friedman, Figure 4.5).

With the high magnitude vibration, there was a significant effect of frequency on the relative difference thresholds (*p* = 0.040; Friedman). The median relative difference threshold increased with increasing frequency from 2.5 to 40 Hz and then decreased with increasing frequency to 315 Hz (Figure 4.5). The relative difference thresholds were significantly greater at 10 Hz than at 2.5 and 5 Hz ($p < 0.017$; Wilcoxon), and significantly greater at 40 Hz than at 2.5 and 315 Hz ($p < 0.028$; Wilcoxon).

4.3.2. Effect of vibration magnitude

The relative difference thresholds were dependent on the magnitude of vibration only at 2.5 Hz ($p = 0.014$; Friedman) and at 315 Hz ($p = 0.004$; Friedman, Figure 4.6). At 2.5 Hz, relative difference thresholds obtained with the high magnitude vibration were lower than those obtained with both the middle magnitude (p = 0.009, Wilcoxon) and the low magnitude ($p = 0.034$, Wilcoxon). Similarly, at 315 Hz, the relative difference thresholds with the high magnitude were lower than those obtained with both the middle magnitude ($p = 0.003$, Wilcoxon) and the low magnitude ($p = 0.001$, Wilcoxon).

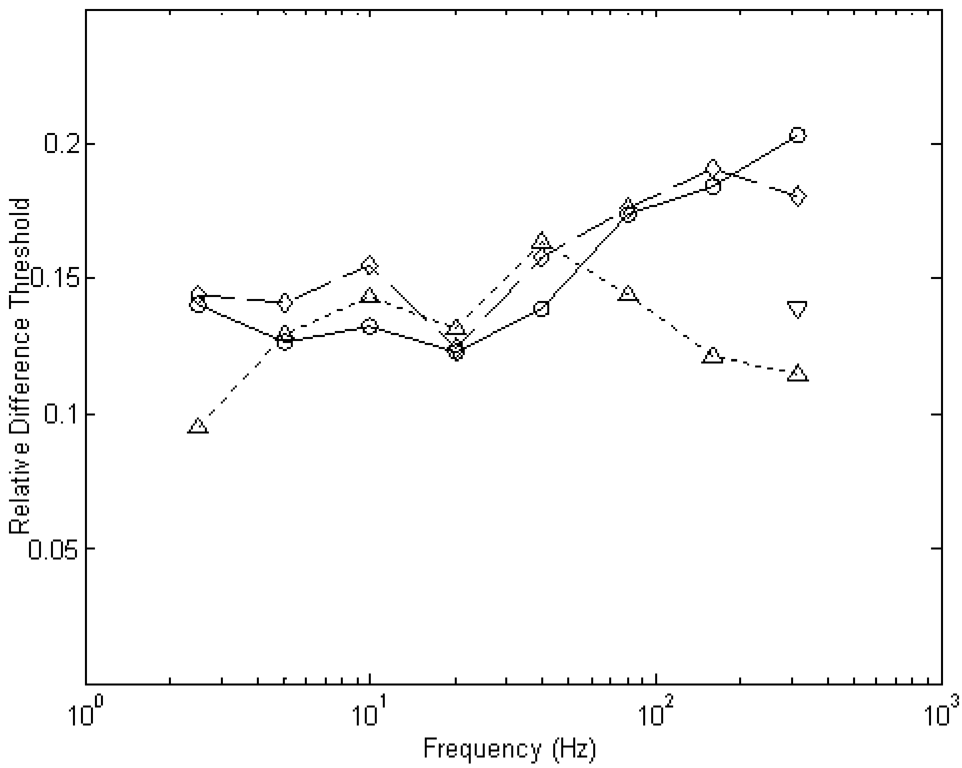
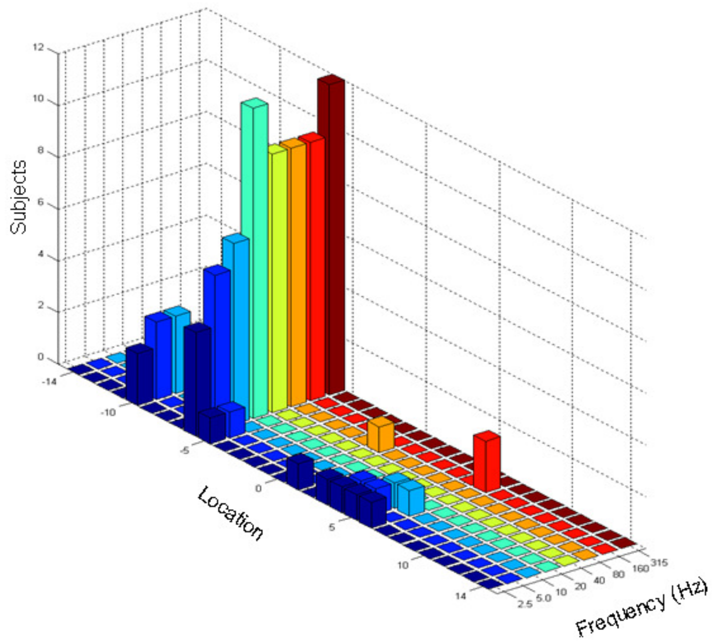


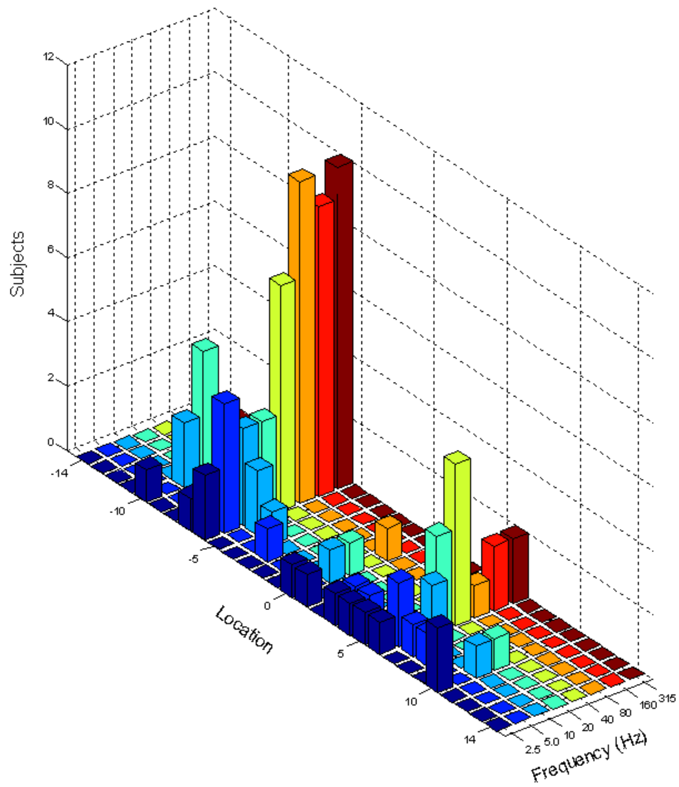
Figure 4.6. Comparison of relative difference thresholds (relative difference thresholds). Vibration stimuli: ○ low magnitude, ◊ medium magnitude, Δ high magnitude. ∇ hearing 315-Hz stimulus at highest magnitude.

With the high magnitude vibration at 315 Hz, there was no significant difference between the relative difference thresholds obtained when feeling the vibration and when only hearing the vibration ($p = 0.424$, Wilcoxon). The relative difference thresholds obtained when only hearing the high magnitude vibration were significantly lower than the relative difference thresholds obtained when feeling both the middle magnitude vibration (p = 0.016, Wilcoxon) and the low magnitude vibration (p = 0.034, Wilcoxon, Figure 4.6).

4.3.3. Location of sensation

The locations of vibration sensation by frequency are given in Figure 4.7.





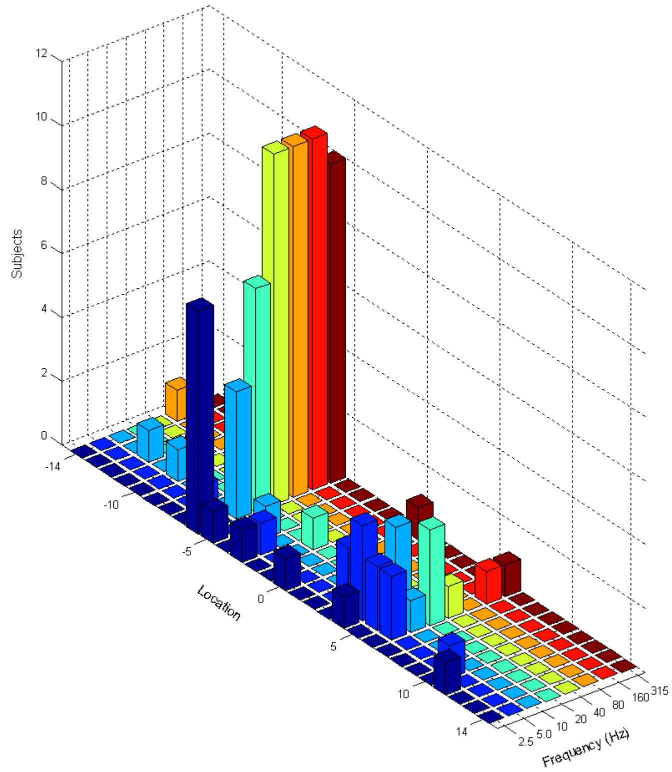


Figure 4.7. Locations of vibration sensation. From top to bottom: Low, Middle and High magnitude conditions.

Figure 4.7 shows that the locations of vibration sensation are dominated by the -6 location (i.e. the buttocks, see Figure 4.4), for frequencies of 40 Hz and higher. A less homogenous distribution is seen for lower frequencies, especially for middle and high magnitudes.

4.4. DISCUSSION

The median relative difference thresholds determined in this study are broadly similar to those obtained with more restricted ranges of vibration frequency and magnitude. Morioka and Griffin (2000) obtained relative difference thresholds of 0.12 at 5 Hz and 0.11 when using 20 Hz vibration at 0.1 ms^{-2} rms. With a similar method and similar stimuli, this study obtained 0.13 at 5 Hz and 0.12 at 20 Hz with the low magnitude vibration (0.05 ms^{-2} r.m.s.). With a similar method but four vertical vibrations recorded on a car seat (reproduced at weighted magnitudes between 0.2 and 0.8 ms^{-2} r.m.s.), Mansfield and Griffin (2000) found median relative difference thresholds of 0.13, 0.14, 0.12, and 0.14, similar to the median of the three median relative difference thresholds over the three vibration magnitudes used in this study (i.e. 0.14).

Bellmann *et al*. (2000) reported relative difference thresholds between 0.15 and 0.20 for 10, 20, and 40 Hz when using vertical vibration at 0.063 ms^{-2} r.m.s., somewhat higher than the 0.12 (at 20 Hz) and 0.14 (at 40 Hz) obtained in the present experiment. The seating conditions used by Bellmann *et al*. differed from the posture in the present experiment.

They had the feet and backs of subjects in contact with vibration: the different distribution of vibration within the body may have been the cause of the higher relative difference thresholds than in the present study.

Matsumoto *et al*. (2002) found relative difference thresholds in the range 0.05 to 0.06 at 4, 8, 16, 31.5, 63, and 80 Hz when using 0.7 ms^{-2} r.m.s. vertical vibration. The psychophysical method used by Matsumoto *et al*. was the method of limits estimating difference thresholds with a probability of correct response at 50%, lower than other studies. This would be expected to give lower difference thresholds, and Matsumoto *et al*. attributed the differences between their results and those of others to the use of this psychophysical method.

The inter-quartile ranges (i.e. the difference between the 75th percentile and 25th percentiles) of the relative difference thresholds are shown in Figure 4.5. The median inter-quartile range in this experiment (about 0.08) is similar to that reported by Morioka and Griffin (2000) (about 0.07) who used a similar method. The data from Bellmann *et al*. (2000) show a median standard deviation of about 0.09. The spread shown in the data from Matsumoto *et al*. (2002) is lower (about 0.03).

4.4.1. Effect of vibration frequency

The trend towards greater relative difference thresholds at higher frequencies than at lower frequencies with both the low and medium vibration magnitudes might be associated with the frequency-dependence of either the transmissibility of the body or the perception of vibration, or both. At low frequencies vertical vibration is transmitted to the upper parts of the body, whereas at high frequencies the vibration is sensed mostly around the seat contact area, the lower body and thighs (Whitham and Griffin, 1978). In the four-channel theory of vibrotactile perception at the glabrous skin of the hand, at frequencies greater than about 40 Hz the P channel becomes more sensitive than the NPI channel (Gescheider *et al*., 1985; Verrillo and Bolanowski, 1986). At low magnitudes, difference thresholds may therefore be determined within the NPI channel at low frequencies and within the P channel at high frequencies. At very low frequencies, less than about 4 Hz, the NPIII channel may be more sensitive than the NPI channel. A tendency for the relative difference thresholds to be greater at higher frequencies would be consistent with the P channel having a greater relative difference threshold than the other two channels. This is consistent with the suggestion of Gescheider *et al*. (1997a) arising from a study of the effect of temperature (Section 2.4.6) on vibrotactile difference thresholds on the hand, although an earlier study failed to find channel-specific differences in relative difference thresholds (Gescheider *et al*., 1990).

4.4.2. Effect of vibration magnitude

The frequency-dependence of relative difference thresholds might reasonably be expected to depend on the magnitude of vibration. The low magnitude in the current experiment was about 10 dB above the absolute threshold from 2.5 to 80 Hz, and about 5 dB above the absolute threshold at 160 and 315 Hz (relative to absolute thresholds reported by Parsons and Griffin, 1988). At these magnitudes, perception may be restricted to the response of one channel (either NPIII, NPI, or P depending on frequency). The middle magnitude was between 25 and 15 dB above the absolute threshold, and the high magnitude between 35 and 25 dB above the absolute threshold. At these higher magnitudes, perception is likely to be mediated by more than one channel. However, in the present experiment with vertical whole-body vibration, a significant difference in relative difference thresholds due to vibration magnitude was only found at 2.5 Hz and 315 Hz. At 80 and 160 Hz, although the effect of vibration magnitude was not statistically significant, the median relative difference thresholds obtained with the higher magnitude vibration were lower than those obtained at the two lower magnitudes, consistent with the trend at 315 Hz.

The magnitude-dependence of the difference thresholds at low and high frequencies in this experiment may have arisen from perception via sensory channels other than tactile channels. At 2.5 Hz, the motion could be seen, especially at the higher magnitude. The lower difference threshold with high magnitude vibration at 2.5 Hz may have arisen because at this magnitude the difference became more obvious via vision than by feeling. The reference magnitude of 0.8 ms^{-2} r.m.s. at 2.5 Hz corresponds to a peak-to-peak displacement of 9.2 mm, so the difference threshold of about 0.10 at that frequency corresponds to a 0.9 mm change in the peak-to-peak displacement at the seat. Subjects were able to see apparent movement between objects in the foreground and objects in the background and the results suggest they were able to discern the intensity difference by seeing the movement, but there are no known studies of difference thresholds for the visual perception of this type of movement.

Similarly, the lower difference thresholds at 315 Hz may have arisen because subjects were able to hear the stimulation at this frequency, especially at the higher magnitude, and they may have found the auditory differences more apparent than the tactile differences. Some subjects may have also heard the motion of the vibrator at 160 Hz, either through acoustic noise or through bone conduction.

According to Turner *et al.* (1989), relative difference thresholds for detecting differences in sound pressure level at 500 Hz decrease from about 1.5 dB (i.e. 0.19) in sound intensity at 20 dB above the absolute threshold to about 0.5 dB (0.06) at 80 dB above the absolute threshold, when determined by a gated-pedestal method. At 60 dB SL, the difference threshold is about 1 dB, giving a relative difference threshold of 0.12. This relative difference threshold is less than measured for the low and middle vibration magnitudes at 315 Hz (0.20 and 0.18, respectively). The relative difference threshold obtained when only hearing the 315-Hz stimulus in the current experiment was 0.14, similar to that obtained for 500 Hz sound at 60 dB by Turner *et al*. (1989).

4.5. CONCLUSIONS

Median relative difference thresholds for vertical whole-body vibration of seated persons in the frequency range 2.5 to 315 Hz vary between 0.09 and 0.20, similar to those previously reported for a more restricted range of vibratory stimuli.

The relative difference thresholds tended to be lower at low frequencies (from 2.5 to 20 Hz) than at higher frequencies (from 40 to 315 Hz), possibly due to differences in the location in the body where vibration was felt or differential mediation by non-Pacinian and Pacinian channels.

At 2.5 Hz, where changes in the magnitude of vibration may be more easily seen, and at 315 Hz where changes can be heard, the relative difference thresholds may be lower than at intermediate frequencies where the changes can only be felt.

The results from this first experiment indicate that for most of the investigated conditions no frequency or magnitude effects exist. However, it was not possible to rule out somatosensory channel-dependence from the results of this experiment. New experiments with conditions where it would be easier to isolate and identify the somatosensory system involvement are needed to achieve the goals of the thesis.

CHAPTER 5: DIFFERENCE THRESHOLDS OF HAND-TRANSMITTED VIBRATION

5.1. INTRODUCTION

Experiment I (detailed in Chapter 4), produced some interesting results, and it was concluded that experiments focusing on somatosensory channel mediation were needed. In earlier studies by other researchers, somatosensory channel mediation has mostly been studied on the glabrous skin of the hand, where knowledge includes frequency response models of absolute thresholds for hand-transmitted vibration. This knowledge is helpful in discussing somatosensory channel mediation effects. A study focusing on hand-transmitted vibration was therefore designed as the second experiment.

There have been few earlier studies of the effects of the magnitude of hand-transmitted vibration on difference thresholds. For two magnitudes of hand-transmitted vibration (2.0 and 5.0 ms^{-2} r.m.s.) at each of seven frequencies (preferred octave centre frequencies from 8 to 500 Hz), Morioka (1998) found relative difference thresholds between 0.16 and 0.19. There were no statistically significant differences in relative difference thresholds between vibration frequencies, or between vibration magnitudes at any frequency. However, at higher frequencies such as 125, 250 and 500 Hz, the relative difference thresholds were slightly greater at the low magnitude (mean 0.19) than at the high magnitude (mean 0.16). The psychophysical method and the hand-grasping posture were similar to those employed in the present study.

Some studies have found that, contrary to Weber's Law, difference thresholds for vibration depend on vibration magnitude (Section 2.4.4.2).

According to Craig (1972), Spector (1954) found that at vibration magnitudes less than 15 dB SL (i.e. 15 dB above the absolute perception threshold), the relative difference threshold decreased as the vibration magnitude increased. Craig (1972) used 200-millisecond sinusoidal 160-Hz vibration, applied to the fingertip through a 6-mm diameter circular contactor to obtain difference thresholds at four vibration magnitudes (14, 21, 28, and 35 dB SL). The relative difference thresholds were constant at about 0.16 at all four magnitudes.

Gescheider *et al*. (1990) reported reductions in difference thresholds with increasing vibration magnitude (from about 0.26 at 4 dB SL to 0.12 at 40 dB SL), using 25 and 250 Hz sinusoidal stimuli applied by a 2.9 cm^2 contactor at the thenar eminence of the hand. The relative difference thresholds were similar for both frequencies (differing by less than about 0.05). Gescheider *et al*. (1996a) found that difference thresholds for 250 Hz sinusoidal vibration applied to the thenar eminence decreased from about 0.26 at 4 dB SL to 0.16 as the vibration magnitude increased to 36 dB SL.

The current experiment examined the effects of vibration magnitude (from 6 to 36 dB above absolute perception thresholds) on intensity difference thresholds for 16 and 125 Hz vertical sinusoidal hand-transmitted vibration. Low magnitudes of vibration at 16 Hz were expected to be detected by a non-Pacinian channel (most likely NPI), while low magnitudes of vibration at 125 Hz were expected to be detected by the Pacinian channel. As the vibration magnitude increased, other receptors were expected to respond (Bolanowski *et al*., 1988; Pasterkamp, 1999; Gescheider *et al*., 2001). Difference thresholds were expected to depend on vibration magnitude due to the involvement of different psychophysical channels at different magnitudes. At low magnitudes, the difference thresholds were expected to differ between the two test frequencies due to the involvement of the different channels.

5.2. METHOD

5.2.1. Subjects

Twelve healthy male subjects (aged 20 to 28 years, mean stature of 177.8 cm, mean weight 72.5 kg) participated in the study that was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

Each subject attended two sessions. In each session, the absolute perception threshold and six difference thresholds were obtained for the right hand at one of the two frequencies (either 16 or 125 Hz). Absolute perception thresholds were determined at the beginning and the end of each session.

The skin temperature of the right hand was measured and the experiment proceeded only if the temperature was greater than 28℃, since the temperature is known to affect absolute perception thresholds mediated by the Pacinian channel (Verrillo and Bolanowski, 1986).

Auditory masking (white noise at 80 dBA) was presented via earphones to mask any auditory cues or distractions. Subjects were given written instructions (Appendix A).

5.2.2. Apparatus

Vertical vibration of the hand was applied via a 30-mm diameter rigid metal handle secured to a MB Dynamics electro-dynamic vibrator. Vibration was measured on the vibrating handle using a piezo-electric accelerometer. The seated subjects were instructed to grip the handle comfortably, and to apply constant grip force during the experiment (Figure 5.1).

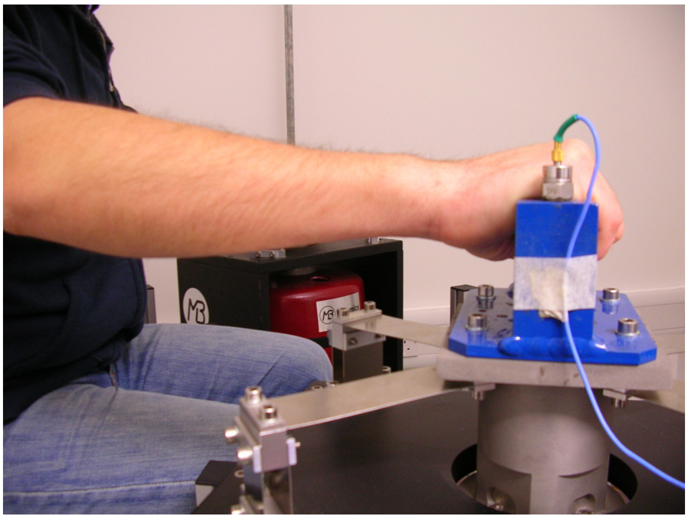


Figure 5.1. Handle-grasping posture.

Vibration was produced and measured using a HVLab data acquisition and analysis system (version 3.81). The signals from a personal computer were generated at 5000 samples per second and passed through a 300 Hz low-pass filter. Mathworks MATLAB software (version 7.0.4.365.R14) was used to analyse the results. A diagram of the experimental setup is given in Figure 5.2.

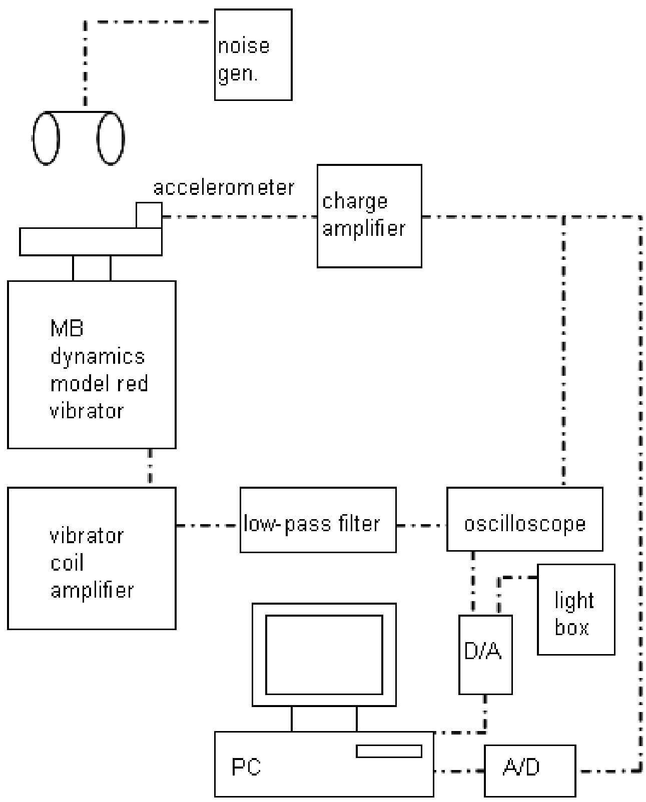


Figure 5.2. Set-up used in Experiment II.

5.2.3. Stimuli

Difference thresholds were determined at six magnitudes above the absolute perception thresholds of each subject (i.e. at 6, 12, 18, 24, 30, and 36 dB sensation level). The required vibration magnitudes were calculated after the initial determination of the absolute threshold. Over the 12 subjects, the six difference thresholds for each subject were determined in a balanced order.

5.2.4. Psychophysical method

The up-down-transformed-response, UDTR method Wetherill and Levitt (1965) was used to obtain the absolute perception thresholds and the difference thresholds. The UDTR method is a variant of the method of limits, where the magnitude of the test stimulus is increased or decreased depending on the responses of the subject.

The stimuli were presented with a two-interval forced-choice procedure. Each stimulus lasted 2 seconds with 0.5-second rise and decay times. A red light was used to indicate the intervals during which stimuli were presented.

Responses of a subject were tracked using the three-down-one-up rule. When the subject gave three consecutive correct answers, the magnitude of the test stimulus was reduced by a step. When the subject gave an incorrect answer, the magnitude was increased one step.

In the difference threshold determination test, both intervals contained vibration stimuli: the test stimulus and the reference stimulus. The order of the test stimulus and the reference stimulus was randomly determined. The reference and test signals were separated by a 1-second pause. The test vibration was always stronger than the reference vibration, with a difference of at least 0.25 dB, and depended on the responses of the subject as determined by the three-down-one-up rule. The subjects were asked to identify the interval that contained the stronger stimulus.

A difference threshold was obtained from:

$$\text{difference threshold} = \frac{\sum_{i=3}^{N=6}(M_i - R_i)}{(N-2)} \tag{5.1}$$

where N is the number of reversals (N=6), M_i and R_i are, respectively, the measured r.m.s. acceleration magnitude of the test vibration and the measured r.m.s. acceleration magnitude of the reference vibration.

To determine a relative difference threshold (i.e. a relative difference threshold), the absolute value of the difference threshold for that stimulus was divided by the r.m.s. acceleration magnitude of the measured reference vibration magnitude, R_i:

$$\text{relative difference threshold} = \frac{\sum_{i=3}^{N=6}(M_i - R_i)}{R_i \cdot (N-2)} \tag{5.2}$$

The absolute perception thresholds were measured using the same psychophysical method, except that the test stimulus was present in only one of the intervals and the step size was 3 dB.

5.3. RESULTS

The median absolute thresholds at the commencement of the experiment were 0.108 ms^{-2} r.m.s. (range 0.062 to 0.173 ms^{-2} r.m.s.) at 16 Hz and 0.016 ms^{-2} r.m.s. (range 0.011 to 0.024 ms^{-2} r.m.s.) at 125 Hz. The median 16-Hz thresholds significantly increased from 0.108 to 0.14 ms^{-2} r.m.s. (range 0.09 to 0.21 ms^{-2} r.m.s.) between the beginning and end of the experiment ($p = 0.0049$; Wilcoxon, Figure 5.3). The median 125-Hz thresholds decreased from 0.016 to 0.014 ms^{-2} r.m.s. (range 0.011 to 0.022 ms^{-2} r.m.s., Figure 5.4) between the beginning and end of the experiment, although the difference was not statistically significant ($p = 0.4238$; Wilcoxon).

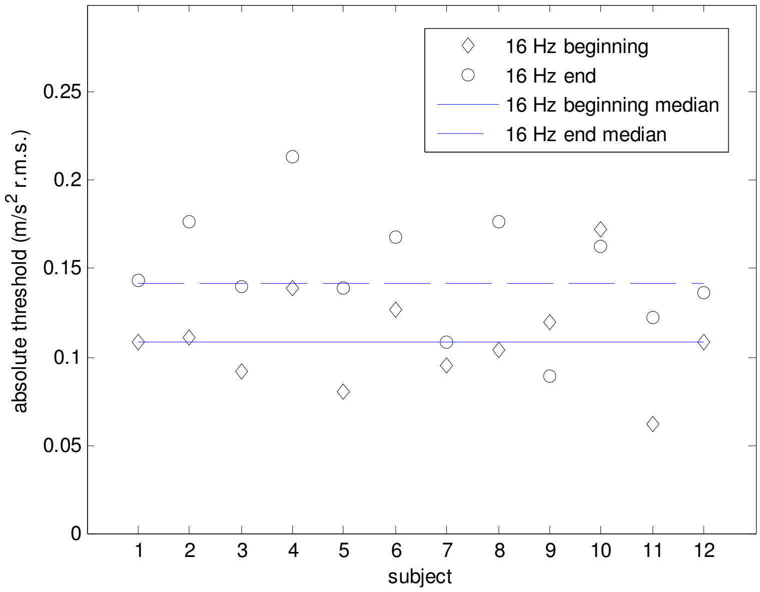


Figure 5.3. 16-Hz absolute thresholds and medians, measured at the beginning and the end of sessions.

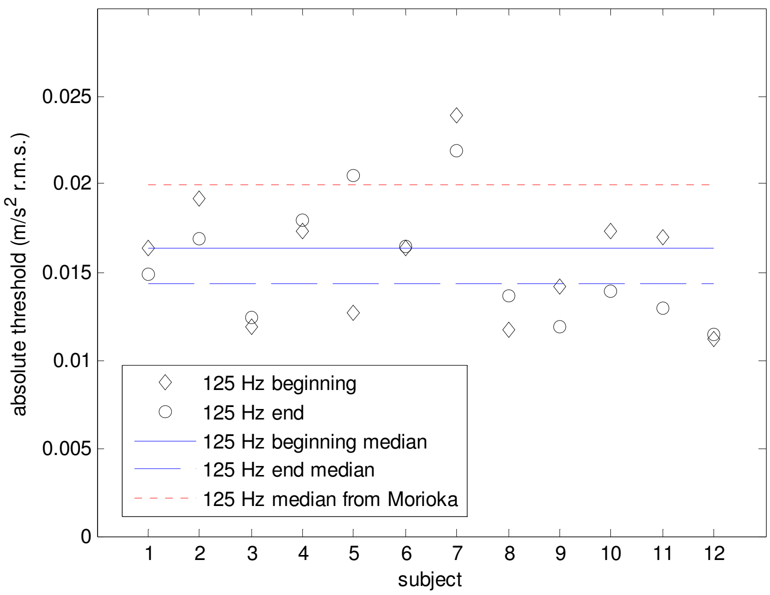


Figure 5.4. 125-Hz absolute thresholds and medians, measured at the beginning and the end of sessions. Median threshold from Morioka (2001) is also shown for comparison.

The median absolute difference thresholds increased with increasing vibration magnitude (Figure 5.5). The median relative difference thresholds were in the range 0.17 to 0.20 for vibration at 16 Hz and in the range 0.15 to 0.23 for vibration at 125 Hz (Figure 5.6).

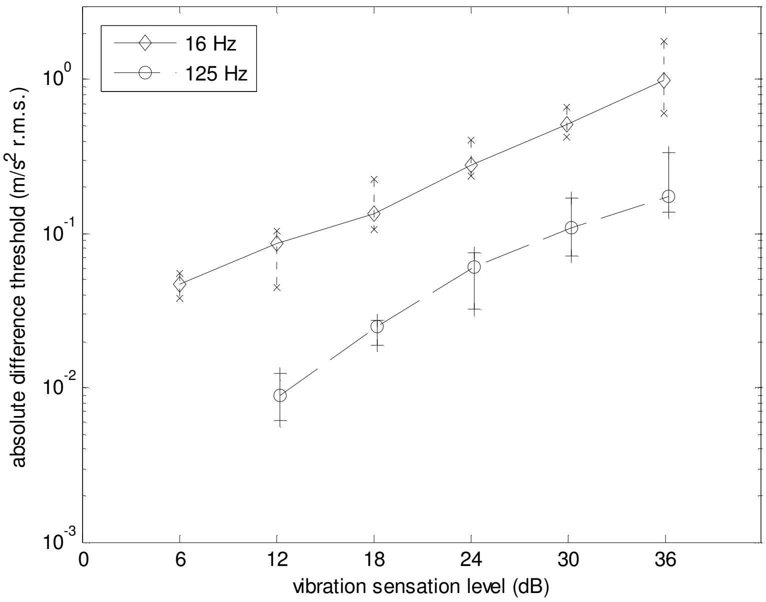


Figure 5.5. Median absolute difference thresholds for 16-Hz and 125-Hz vibration at six sensation levels and interquartile ranges.

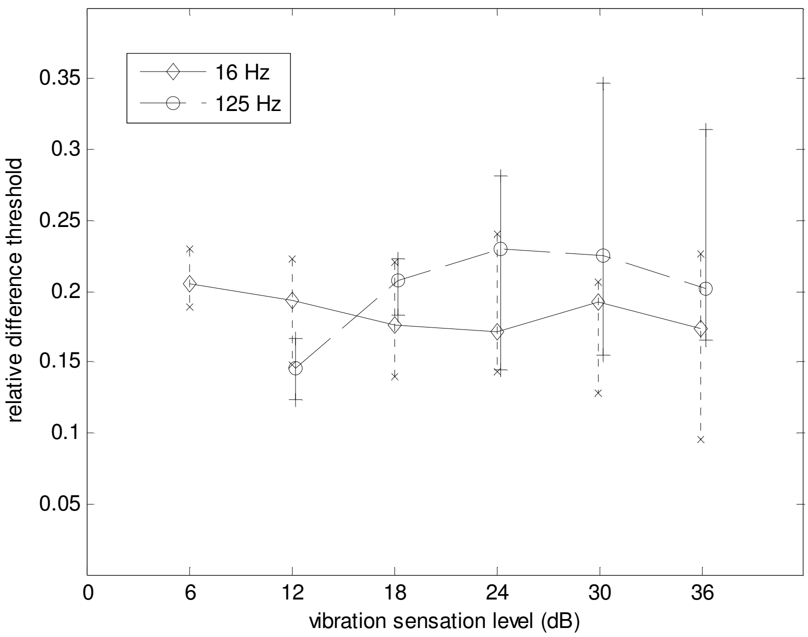


Figure 5.6. Median relative difference thresholds for 16-Hz and 125-Hz and interquartile ranges.

The relative difference thresholds for 125-Hz vibration were lower than the relative difference thresholds for 16-Hz vibration at the 12 dB SL reference magnitude, but higher at higher reference magnitudes, although the differences were not statistically significant at any reference magnitude ($p > 0.11$, Wilcoxon).

The 16-Hz difference thresholds were not significantly affected by vibration magnitude ($p = 0.6270$; Friedman) but the 125-Hz difference thresholds were dependent on vibration magnitude ($p = 0.0002$; Friedman). The 125-Hz relative difference threshold at 12 dB SL was significantly less than that at the three highest reference magnitudes ($p \leq 0.009$; Wilcoxon). The relative difference threshold at 12 dB SL was also marginally non-significantly lower than the relative difference threshold at 18 dB SL ($p = 0.064$, Wilcoxon), at 125 Hz.

The 125-Hz difference thresholds at 6 dB SL may have been biased low as the increments in the magnitude of the test stimuli were lower than intended due to equipment limitations at low magnitude. The measured relative difference threshold for 125-Hz vibration at 6 dB SL was 0.09, and significantly less than that at all other magnitudes of 125 Hz ($p \leq 0.0161$; Wilcoxon), except the magnitude at 12 dB SL, which was marginally non-significantly higher ($p = 0.0522$; Wilcoxon). The relative difference threshold for 125-Hz vibration was significantly less than that for 16-Hz vibration at 6 dB SL ($p = 0.0269$; Wilcoxon).

Over the six vibration magnitudes, there were no significant correlations between the relative difference thresholds within the same frequency and no significant correlations between relative difference thresholds across frequencies.

There were no statistically significant correlations between the absolute perception thresholds and the relative difference thresholds. There were no significant correlations between the relative difference thresholds and the age or stature of the subjects. Due to the large number of correlations, their significance was judged using a criterion of $p < 0.01$ (Spearman).

5.4. DISCUSSION

There was no significant effect of vibration magnitude on the relative difference thresholds at 16 Hz, so it may be concluded that they conform to Weber's Law over the range of magnitudes investigated.

The relative difference thresholds at 125 Hz increased with increasing magnitude up to 18 dB SL. This increase from lower magnitudes (6 and 12 dB SL) to higher magnitudes (18 dB SL to 30 dB SL) may have arisen from the involvement of different somatosensory channels at different vibration magnitudes. Although only the Pacinian channel mediates perception just above the absolute perception threshold, other channels mediate perception at higher magnitudes (Bolanowski *et al.*, 1988; Gescheider *et al.* 2001). In the four-channel model of Bolanowski *et al.* (1988), a stimulus magnitude of about 20 dB SL may be sufficient at 125 Hz to activate non-Pacinian channels. The difference in relative difference thresholds between the low magnitudes and the high magnitudes might have arisen from excitation of non-Pacinian receptors at magnitudes greater than about 18 dB SL.

The increase in the 125-Hz relative difference thresholds with increasing vibration magnitude could suggest that at vibration magnitudes greater than about 15 dB SL the ability of the Pacinian system to discriminate differences in vibration magnitude became 'saturated' (Bolanowski and Zwislocki, 1984), so that differences were more easily detected by a non-Pacinian channel. The results suggest that any such saturation occurred at a magnitude of 125-Hz vibration greater than the absolute threshold of the non-Pacinian channel at this frequency.

With 125-Hz vibration applied to a small area of the thenar eminence, different results have been found from those reported here for the whole hand. Gescheider *et al.* (1990, 1996a) reported a 'near miss' to Weber's Law – the difference thresholds decreased slightly with increasing vibration magnitude (at 0.015 dB per dB increase in sensation level) over vibration magnitudes from 14 dB SL to 40 dB SL.

There are several differences between the present study and the studies by Gescheider *et al.* (1990, 1996a, 1996b, 1997a). They employed different types of subjects (a smaller number of trained subjects of both genders aged 20 to 57), different psychophysical methods, and stimuli having a different frequency, duration (0.7 s), and input location. With the vibration applied by a small contactor to the thenar eminence for 0.7 s there would have been far less excitation of the Pacinian channel than with vibration of the whole hand for 2.0 s in the current study. This may have resulted in 'saturation' of the Pacinian channel in the present study at lower vibration magnitudes than investigated by Gescheider *et al.* (1990, 1996a).

The absence of an effect of age on the relative difference thresholds is consistent with the findings of Gescheider *et al.* (1994b) who reported 'when the difference limen was expressed in relative terms as the proportion by which two stimuli had to differ in amplitude to be discriminated, discriminative capacities were unaffected by aging except for stimuli slightly above the detection threshold, in which case the limens of older subjects were significantly higher than those of younger subjects'.

5.5. CONCLUSIONS

The relative difference threshold for 16-Hz vertical vibration of the hand in a hand-grasping posture is in the range 0.17 to 0.20 and independent of vibration magnitude when the vibration magnitude is 6 dB to 36 dB above the absolute threshold of perception.

The relative difference threshold for 125-Hz vertical vibration of the hand in a hand-grasping posture is in the range 0.15 to 0.23, increasing with increasing magnitude from 12 dB to 18 dB above the absolute threshold of perception but independent of vibration magnitude from 18 to 36 dB above the absolute threshold of perception.

There were no significant differences between the relative difference thresholds that were likely to have been mediated by the NPI and P channels, although the P-channel relative difference threshold (at 12 dB SL, 125 Hz) was slightly smaller than the NP-I channel relative difference thresholds (12 dB SL, 16 Hz).

The findings of Experiment II, such as the magnitude-dependence of the relative difference thresholds (especially at 125 Hz) and the possible somatosensory channel-dependence merit further consideration. This was accomplished by determining relative difference thresholds at the foot, which is anatomically similar to hand, in the next experiment.

CHAPTER 6: DIFFERENCE THRESHOLDS OF FOOT-TRANSMITTED VIBRATION

6.1. INTRODUCTION

Having obtained relative difference thresholds for whole-body (Chapter 4) and the hand (Chapter 5), it seemed appropriate and useful to investigate relative difference thresholds for another input location. Foot-transmitted vibration was considered interesting as it is a common source of vibration discomfort and it would provide difference thresholds on glabrous skin which could be compared to those from the glabrous skin of the hand. Also, since there are no known studies of relative difference thresholds for foot-transmitted vibration, the measurement of thresholds would help to develop a more complete picture of human difference threshold perception. The design of the third experiment was based on the design of Experiment II, although the two designs are not identical because the design of Experiment III took into account the experience gained from Experiment II.

Four ‘channels’ appear to be involved in the perception of vibration applied to the glabrous skin, with the absolute threshold for vibration perception being mediated by different channels at different frequencies (Bolanowski *et al*., 1988; Gescheider *et al*., 2001). Studies of the perception of vibration at the thenar eminence on the hand suggest that absolute thresholds for the perception of vibration at frequencies less than about 2 Hz are likely to be mediated by the ‘non-Pacinian III channel’. At frequencies between about 2 and 40 Hz, the ‘non-Pacinian I channel’ probably mediates absolute thresholds. At frequencies greater than about 40 Hz, absolute thresholds are mediated by the ‘Pacinian channel’, which has a sensitivity to displacement of the skin that increases with increasing frequency up to about 250 Hz and then declines. The fourth channel, ‘non-Pacinian II channel’, has greatest sensitivity to displacement in a frequency range similar to the P channel, but with a sensitivity less than the P channel in most contact conditions. While the channels responsible for absolute thresholds have been suggested, the mechanisms responsible for the perception of changes in magnitude at supra-threshold levels, and whether the difference threshold depends on the channel mediating the sensation of vibration, is less clear.

For the hand, some studies have found that relative difference thresholds depend on the magnitude of vibration, contrary to Weber's Law. With 25-Hz and 250-Hz sinusoidal vibration applied by a 2.9 cm^2 contactor to the thenar eminence of the hand, Gescheider *et al.* (1990) found reductions in relative difference thresholds with increasing vibration magnitude (from 0.26 at 4 dB SL to 0.12 at 40 dB SL, where SL is the sensation level – the level of the vibration stimulus expressed relative to the subject's absolute threshold). The relative difference thresholds were similar at the two frequencies (differing by less than about 0.05). With 250-Hz sinusoidal vibration, and contact conditions similar to the 1990 study, Gescheider *et al.* (1996a) found that relative difference thresholds decreased from 0.26 at 4 dB SL to 0.16 at 36 dB SL. Again with 250-Hz vibration and contact conditions similar to the 1990 and 1996 studies, Gescheider *et al.* (1997a) also found reductions in relative difference thresholds with increasing vibration magnitude. Gescheider *et al.* (1990) suggested the reduction could be due to a spread of the vibration excitation at higher magnitudes. However, Gescheider *et al.* (1997a) suggested that reductions in relative difference thresholds may have resulted from the involvement of channels other than the P channel at higher magnitudes, particularly the involvement of the NPII channel. In contrast to the Gescheider studies, with the whole hand gripping a handle vibrating at 125 Hz, Experiment II (Chapter 5, also Forta, 2006) found that relative difference thresholds were greater at high magnitudes (in the range 18 to 36 dB SL) than at low magnitude (12 dB SL).

Few studies have investigated foot-transmitted vibration, and there are no known studies of difference thresholds for the perception of vibration applied to the foot. Equivalent comfort contours showing how the perception of vibration of the whole foot depends on the frequency of vibration at supra-threshold levels have been reported by Parsons *et al.* (1982), Rao (1983), Miwa (1988) and Morioka and Griffin (2008a). Thresholds at specific locations on the foot have also been reported, usually in the context of the detection of sensori-neuropathy (e.g., Vedel and Roll, 1982; Kekoni *et al.*, 1989; Gu and Griffin, 2007). Absolute thresholds for vibration of the entire foot have been reported by Morioka and Griffin (2008b) using 12 subjects and vibration stimuli and contact conditions similar to those in the current experiment (Section 6.2.2). They used sinusoidal vibration and determined absolute thresholds over the frequency range from 8 to 315 Hz. The absolute thresholds for vertical vibration (expressed in terms of acceleration) were independent of frequency from 8 to 25 Hz, but dependent on frequency at higher frequencies, defining a U-shaped contour with the lowest threshold at about 100 Hz, and greatly increased threshold at 200 Hz and 315 Hz. The median thresholds were 0.040 ms^{-2} r.m.s. at 16 Hz and 0.029 ms^{-2} r.m.s. at 125 Hz.

The experiment presented here was designed to investigate the influence of vibration magnitude and vibration frequency on intensity difference thresholds for vertical sinusoidal vibration of the entire foot at 16 Hz and 125 Hz. At vibration magnitudes less than 12 dB SL it was expected that these two frequencies would primarily excite the non-Pacinian I (NPI) and the Pacinian (P) channels, respectively. At these low levels of vibration it was hypothesised that relative intensity difference thresholds for 16-Hz vibration mediated by the NPI channel would differ from those for 125-Hz vibration mediated by the P channel. With both frequencies of vibration, it was expected that relative intensity difference thresholds would change when the vibration magnitude increased above 12 dB SL, as the vibration became sufficient to excite other channels according to the four-channel model of vibrotactile perception (Bolanowski *et al.*, 1988; Gescheider *et al.*, 2001).

6.2. EXPERIMENTAL METHOD

6.2.1. Apparatus

Vibration stimuli were generated and measured using *HVLab* software (version 3.81) running in a personal computer. Signals were generated at 5000 samples per second and passed through a 300-Hz low-pass filter to an MB Dynamics Model SL 500VCF power amplifier connected to a MB Dynamics electro-dynamic vibrator. The vibrator applied vertical sinusoidal vibration to the right foot via a rigid wooden platform inclined by 10 degrees, with the rear lower than the front (Figure 6.2). Vibration was measured using a piezo-electric accelerometer (D.J. Birchall, model A/20T) attached to the footrest. The vibration acceleration signal was acquired via a Techfilter anti-aliasing filter (1000 Hz low-pass) to a PCL-818 12-bit analogue-to-digital converter.

A schematic of the experimental set-up is given in Figure 6.1.

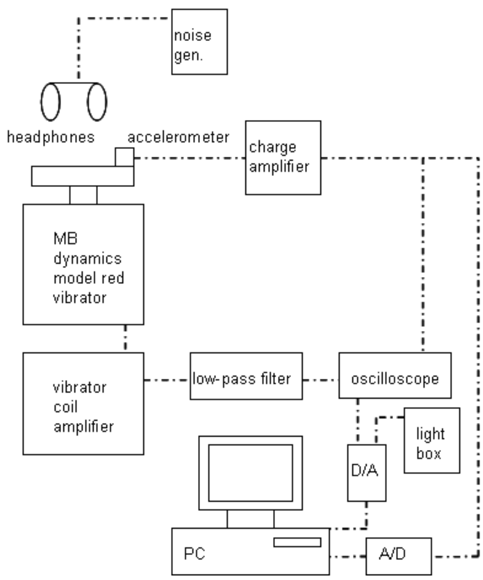


Figure 6.1. The experimental set-up.

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

6.2.2. Procedure

The experiment was conducted in two sessions on different days, each lasting about 75 minutes. Prior to commencing the experiment, subjects removed their shoes and rolled their trousers up above the knee so as to remove any cues due to clothing moving relative to the skin (Figure 6.2). Written instructions given to the subjects are given in Appendix A.

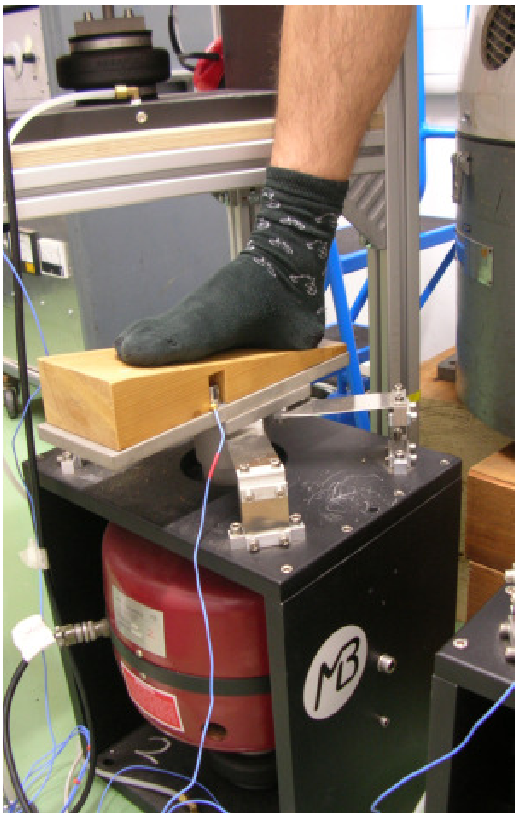


Figure 6.2. Experimental set-up and posture.

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

Both sessions commenced with the measurement of the absolute threshold, used to calculate the six 'reference magnitudes for the difference threshold tests. The locations at which the maximum sensation was experienced when exposed to the reference magnitudes were then determined using a diagrammatic representation of the foot and lower leg (Figure 6.3). After one practice measurement, difference thresholds were then determined at the six reference magnitudes in a Latin square balanced order. After each determination of a difference threshold, subjects were asked to identify the body location where they detected the difference between the two vibration stimuli (Figure 6.3). At the end of each session, the absolute threshold was measured again.

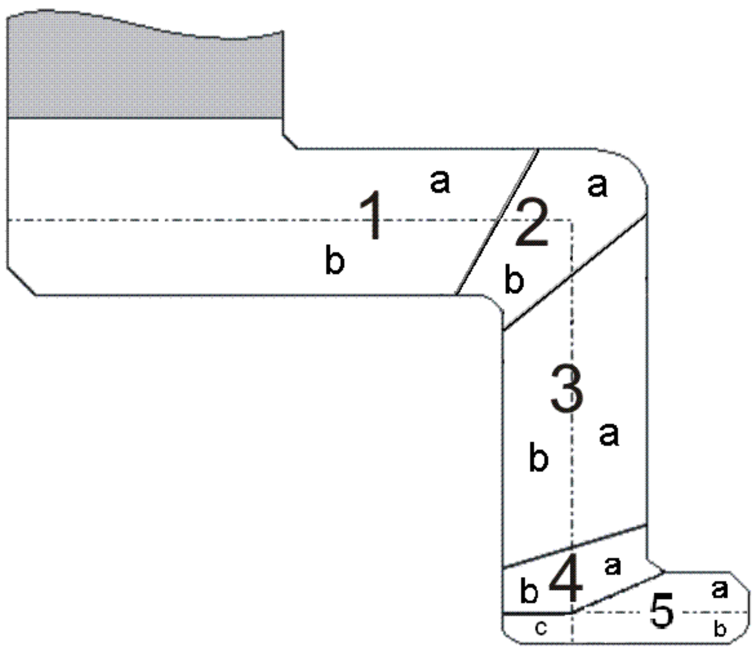


Figure 6.3. Diagrammatic representation of the foot and the lower leg used to determine the locations of vibration sensations and differences in vibration magnitude. Letters a and b distinguish the front and rear parts of the leg and the foot and c maps to the foot sole.

Auditory masking (white noise at 75 dBA) was presented via headphones. The skin temperature of the right foot was measured with a thermocouple at the sole of the foot before and after the measurements, because absolute thresholds are dependent on temperature, especially in the Pacinian channel (Verrillo and Bolanowski, 1986).

6.2.3. Subjects

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

6.2.4. Psychophysical method

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

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

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

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

An absolute difference threshold was calculated using:

$$\text{absolute difference threshold} = \sum_{i=3}^{N=6} \left(\frac{M_i - R_i}{(N-2)} \right) \tag{6.1}$$

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

To determine a relative difference threshold, the absolute value of the difference threshold for that stimulus was divided by the r.m.s. acceleration magnitude of the reference vibration, R_i:

$$\text{relative difference threshold} = \sum_{i=3}^{N=6}\left(\frac{M_i - R_i}{R_i \cdot (N-2)}\right) \qquad (6.2)$$

6.2.5. Statistical methods

Mathworks Inc. MATLAB (R14) software with Statistics Toolbox, was used to calculate the thresholds and perform the subsequent statistical analysis of the results. Non-parametric tests (Friedman and Wilcoxon matched-pairs signed ranks for two-related samples) were employed in the statistical analysis. Cochran's Q and McNemar tests were employed to investigate the location at which vibration was perceived. These tests were conducted using SPSS Inc. SPSS 16.0 software.

6.3. RESULTS

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

6.3.1. Absolute thresholds

Absolute thresholds for 16-Hz vibration were significantly greater than those for 125 Hz vibration at both the beginning and the end of the session (Wilcoxon, p = 0.0005). The median threshold for 16-Hz vibration rose by 21% (i.e. 1.7 dB), from 0.034 ms^{-2} r.m.s. at the beginning of the session to 0.042 ms^{-2} r.m.s. at the end of the session (Wilcoxon, p = 0.0068, Figure 6.4). The median threshold for 125-Hz vibration rose by 30% (2.28 dB), from 0.014 ms^{-2} r.m.s. at the beginning of the session to 0.018 ms^{-2} r.m.s. at the end of the session, but the difference was not statistically significant (Wilcoxon, p = 0.1099, Figure 6.4).

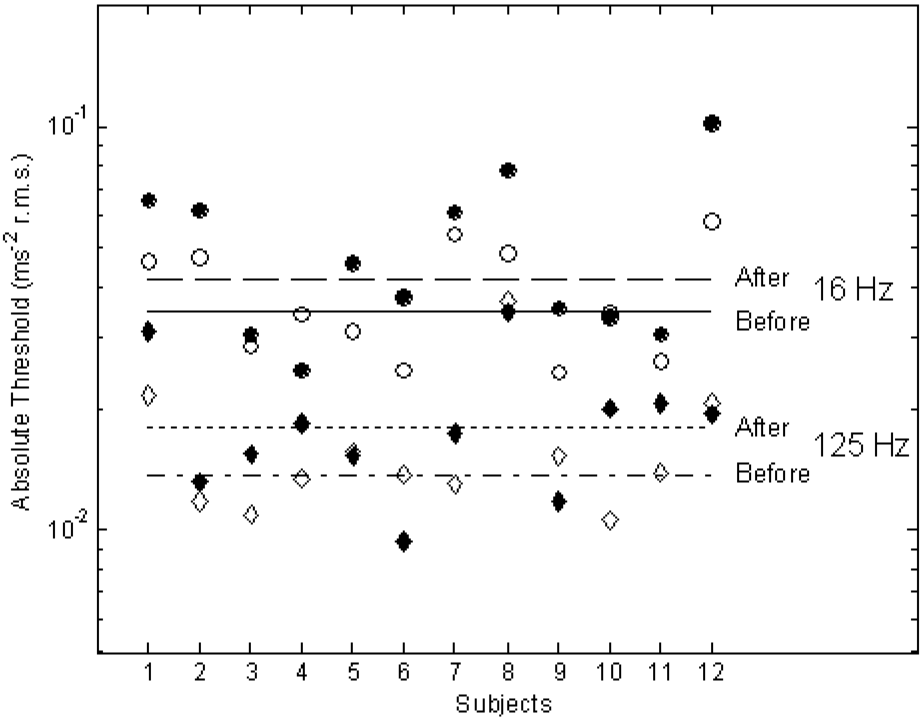


Figure 6.4. Absolute thresholds for vertical vibration at 16 Hz and 125 Hz. Thresholds were measured twice for each subject at each frequency, once before (open points) and once after (closed points) the determination of difference thresholds.

6.3.2. Difference thresholds

As the reference level increased from 6 to 30 dB SL, the median absolute difference thresholds increased from 0.016 to 0.205 ms^{-2} r.m.s. at 16 Hz and from 0.007 to 0.150 ms^{-2} r.m.s. at 125 Hz (Figure 6.5). With 16-Hz vibration, the absolute difference thresholds increased less than predicted by Weber's Law: as the reference magnitude increased by a factor of 16 the difference threshold increased by a factor of 12.5. With 125-Hz vibration, the absolute difference thresholds increased more than predicted by Weber's Law: as the reference magnitude increased by a factor of 16 the difference threshold increased by a factor of 21.

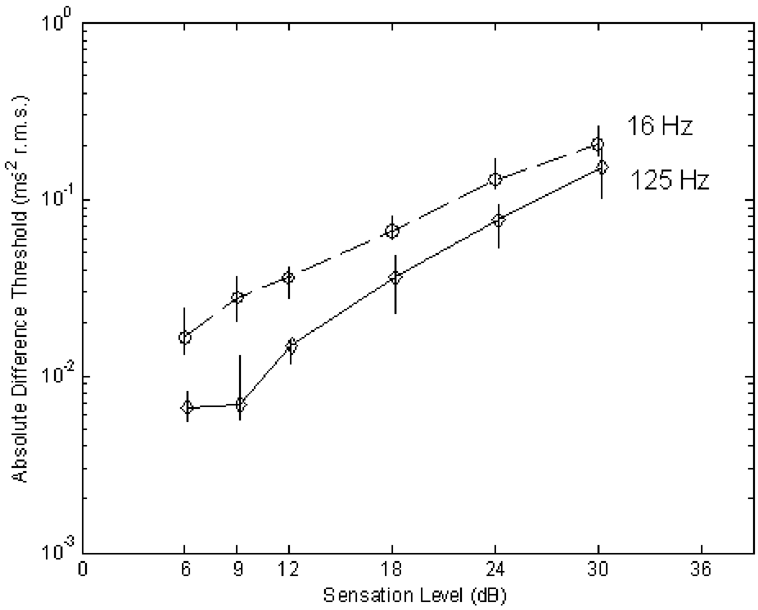


Figure 6.5. Median absolute difference thresholds with inter-quartile ranges for 12 subjects at six sensation levels at 16 Hz and 125 Hz.

With 16-Hz vibration, the median relative difference thresholds varied between 0.19 (at 30 dB SL) and 0.27 (at 9 dB SL). With 125-Hz vibration, the median relative difference thresholds varied between 0.17 (at 9 dB SL) and 0.34 (at 30 dB SL) (Figure 6.6).

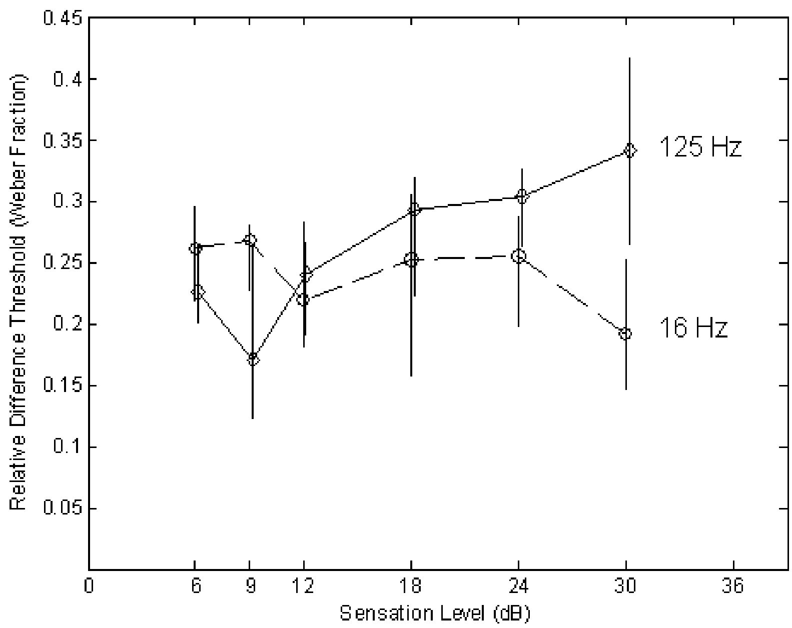


Figure 6.6. Median relative difference thresholds and inter-quartile ranges for 12 subjects at six sensation levels at 16 Hz and 125 Hz.

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

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

Table 6.1. Comparisons between relative difference thresholds for 125-Hz vibration at vibration magnitudes from 6 to 30 dB SL (p-values, Wilcoxon matched-pairs sign ranks test; * p<0.05; ** p<0.01).

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

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

Table 6.2. Comparisons between relative difference thresholds for 16-Hz and 125-Hz vibration at vibration magnitudes from 6 to 30 dB SL (p-values, Wilcoxon matched-pairs sign ranks test; * p < 0.05; ** p < 0.01).

16 Hz	125-Hz					
	6 dB SL	**9 dB SL**	**12 dB SL**	**18 dB SL**	**24 dB SL**	**30 dB SL**
6 dB SL	0.3804	0.1099	0.3394	0.6221	0.2334	0.1099
9 dB SL	0.0425*	0.2334	0.2661	0.6221	0.2661	0.0269*
12 dB SL	0.7334	0.4238	0.8501	0.0771	0.0210*	0.0068**
18 dB SL	0.6221	0.3013	0.9697	0.0522	0.0093**	0.0024**
24 dB SL	0.5186	0.064	0.4697	0.0771	0.0068**	0.0269**
30 dB SL	0.4238	0.791	0.2661	0.0122*	0.0024**	0.0034**

Within the group of 12 subjects, the relative difference thresholds for 16-Hz vibration at 18 dB SL and 125-Hz vibration at 24 dB SL were correlated with each other (Spearman, p = 0.0082), and the relative difference thresholds for 16-Hz vibration at 24 dB SL and 125-Hz vibration at 9 dB SL were correlated with each other (Spearman, p = 0.0004). There were no other significant correlations between relative difference thresholds but all correlations were positive, except those between the 6 dB SL with 16 Hz and 12, 18, 24 and 30 dB SL with 125 Hz, and between 9 dB SL with 16 Hz and 9, 12, 18 and 24 dB SL with 125 Hz vibration. The relative difference thresholds with 16-Hz vibration at 9 dB SL were positively correlated with those with 125-Hz vibration at 30 dB SL.

6.3.3. Location of sensation

The reported locations of sensations were simplified by combining the sub-divisions (indicated by lowercase letters in Figure 6.3) within locations, since all responses at locations 4 and 5 were either on the sole of the foot (5b and 5c) or at the ankle (4b). Only for the lower leg, the knee, and the upper leg were ‘front side’ responses (i.e., 3a, 2a and 1a) observed, but there were few responses in these locations compared to other locations. Overall, ‘back side’ responses were about 90% of the total responses. In Cochran’s Q and McNemar tests, the locations from 1 to 4 were combined and compared to the most common reported location (i.e. location 5 - sole of the foot).

Figure 6.7 shows the reported locations for the strongest sensation. With increasing magnitude of 16-Hz vibration, the sensation of vibration spread from the sole of the foot to the upper part of the foot and the leg. The ratio of the number reporting the strongest sensation at other locations (i.e. 1 - 4) to the number reporting the sole of the foot (i.e. 5) showed a marginally non-significant change with vibration magnitude at 16 Hz (Cochran’s

Q, $p = 0.097$). At 125 Hz, irrespective of vibration magnitude, all subjects indicated that they felt the vibration most at the sole of the foot. Comparing the locations giving the strongest sensations between frequencies at each magnitude (e.g. 16 Hz compared with 125 Hz at 6 dB SL), the locations were not significantly different at the two lower magnitudes (i.e. 6 and 9 dB SL; McNemar, $p = 0.125$ for each case), but they were significantly different at the two middle magnitudes (i.e. 12 and 18 dB SL; $p = 0.031$ for each case), and highly significantly different at the two highest magnitudes (24 and 30 dB SL; $p < 0.009$).

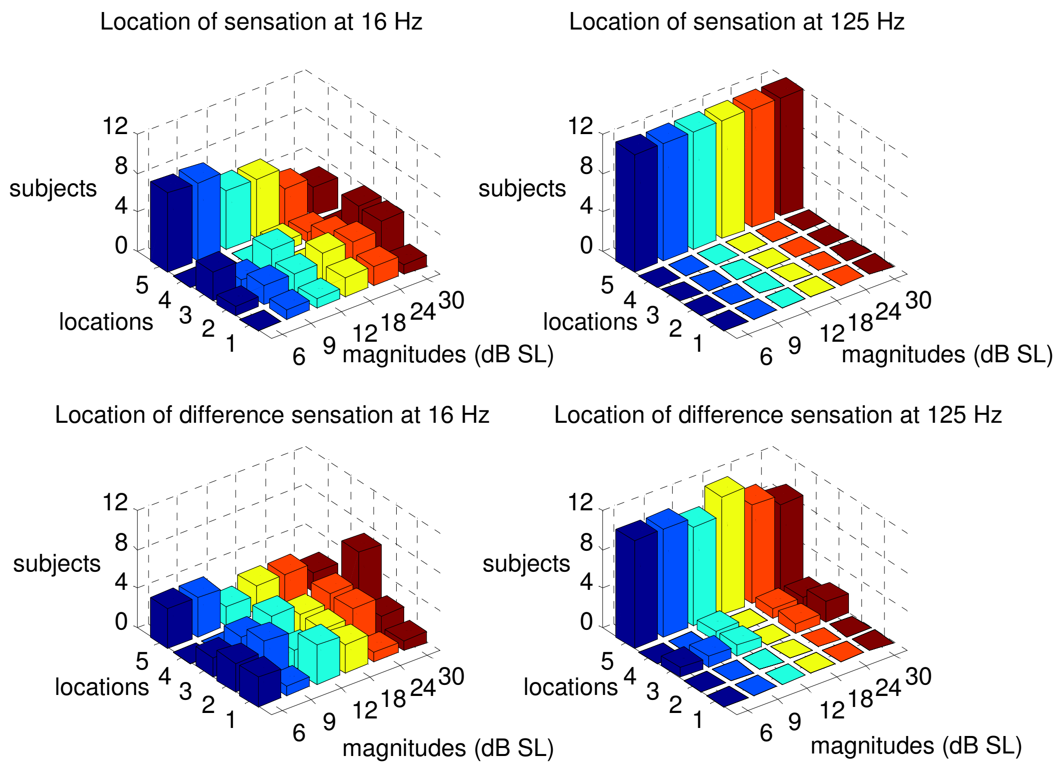


Figure 6.7. Number of reported locations of strongest sensations (top graphs) and difference sensations (bottom graphs).

Figure 6.7 also shows the locations at which subjects reported the differences in sensations that they used to detect differences between the two stimuli (i.e. the locations of the sensations that yielded the difference thresholds). Sensations at the sole of the foot were used for 87.5% of judgements with 125-Hz vibration but only 25% of judgements with 16-Hz vibration. Comparing the locations between frequencies at each magnitude (e.g. 16 Hz compared with 125 Hz at 6 dB SL), the locations differed significantly at all magnitudes (McNemar, $p < 0.017$), with changes in the magnitude of 125-Hz vibration detected at the sole of the foot and changes in the magnitude of 16-Hz vibration detected higher up the leg.

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

6.4. DISCUSSION

6.4.1. Absolute thresholds

Median absolute thresholds obtained at the beginning of the sessions in this experiment were 14% lower at 16 Hz and 53% lower at 125 Hz than those obtained by Morioka and Griffin (2008b). Although the contact conditions and stimuli were similar, different psychophysical methods were employed in the two studies. Morioka and Griffin used a procedure where the subjects indicated when they perceived the vibration in a single interval ('yes-no' procedure). In the current study, subjects had to detect the vibration in one of two intervals ('forced-choice' procedure). Morioka and Griffin (2002) investigated the dependence of vibrotactile thresholds at the fingertip on the psychophysical method and found that the 'forced-choice' procedure significantly lowered thresholds by about 2.2 dB (29% reduction) compared with the 'yes-no' procedure, consistent with the differences observed between the present study and the study by Morioka and Griffin (2008b). As suggested by Morioka and Griffin (2002), the 'yes-no' procedure requires greater certainty of perception compared with the 'forced-choice' procedure.

The 21% rise in 16-Hz thresholds and the 30% rise in 126-Hz thresholds during the experiment suggest that the modest vibration exposures were sufficient to cause temporary threshold shifts. For the subject with the highest thresholds giving the greatest exposures, the 8-h equivalent vibration exposures according to ISO 5349-1 (2001) were less than 0.40 ms^{-2} r.m.s. with 16-Hz vibration and less than 0.03 ms^{-2} r.m.s. with 125-Hz vibration – much lower than the exposure expected to cause injury. The thresholds might have changed as a result of increased experience at the end of the session, but this would be expected to lower rather than raise thresholds. Whatever the cause of the change, it was small relative to the differences in threshold between subjects (see Figure 6.4).

6.4.2. Difference thresholds

Relative difference thresholds most likely to be mediated by the NPI channel (16-Hz vibration at 6, 9 and 12 dB SL, according to Bolanowski *et al.*, 1988) were not significantly different from the relative difference thresholds most likely to be mediated by the P channel (125-Hz vibration at 6, 9 and 12 dB SL, according to Bolanowski *et al.*, 1988), except for one marginal case. Although in the conditions investigated any differences in relative difference thresholds between the two somatosensory channels seem to be small, Figure 6.6 suggests a pattern in which the relative difference thresholds for 125-Hz vibration are less than the relative difference thresholds for 16-Hz vibration at 6 and 9 dB SL but greater as the vibration magnitude increases.

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

The dependence of 125-Hz relative difference thresholds on vibration magnitude may be due to reduced discriminability within the P channel with increased excitation. The neural responses of Pacinian corpuscles saturate at high magnitudes, which may have increased the 125-Hz difference thresholds. Gescheider *et al*. (1997a) reported saturation in the P channel at about 25 dB SL when measuring difference thresholds with 250-Hz vibration applied to the thenar eminence of the hand through a 3-cm^2 contactor. The excitation area and stimulus duration were much greater in the current study and this may have led to saturation of the P channel around 18 dB SL rather than 25 dB SL.

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

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

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

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

The higher magnitudes of 16-Hz vibration were probably above the absolute threshold of the P channel, so if the P channel has greater discriminability than the NPI channel below 12 dB SL (as may be suggested by the results), the relative difference thresholds for the higher magnitudes of 16-Hz vibration could have been mediated by the P channel. In which case, involvement of the P channel at high magnitudes of 16-Hz vibration could have contributed to the downward trend in the 16-Hz relative difference thresholds with increasing magnitude of vibration. If the P channel has a lower relative difference threshold than the NPI channel, a reversal of channels may have taken place: relative difference thresholds for low magnitudes of 16-Hz vibration and high magnitudes of 125-Hz vibration being mediated by the NPI channel and relative difference thresholds for low magnitudes of

125-Hz vibration and high magnitudes of 16-Hz vibration being mediated by the P channel. Such a reversal could cause significant differences between relative difference thresholds obtained with high magnitude 125-Hz vibration and low magnitude 125-Hz vibration, and between high magnitude 125-Hz vibration and high magnitude 16-Hz vibration. Below 12 dB SL, there were no significant differences between the channels, but the P-channel relative difference thresholds (at 125 Hz) tended to be lower than the NPI channel relative difference thresholds (at 16 Hz).

6.4.3. Comparison with other studies

The dependence of relative difference thresholds on the magnitude of vibration in this experiment is similar to that found for 125-Hz hand-transmitted vibration with a hand grip posture, where at vibration magnitudes less than 12 dB SL the relative difference thresholds were significantly less than those at higher magnitudes (Experiment II, Chapter 5, also Forta, 2006). Unlike the studies by Gescheider *et al.* (1990, 1996a, 1997a), but similar to Experiment II of this thesis, the current study reveals lower relative difference thresholds for 125-Hz vibration at lower magnitudes but higher relative difference thresholds at higher magnitudes. Various differences in method may have contributed to the difference in findings. The studies of Gescheider *et al*. involved the application of vibration to small areas of skin at the thenar eminence of the hand whereas the present study applied vibration to the whole foot with the vibration also being transmitted to the leg. Unlike the Gescheider *et al*. studies, the current experiment did not involve a surround around the contactor with a 1-mm gap – conditions that restrict the distribution of vibration and enhance the sensitivity of the NPI channel. With the contact conditions in the current study, the absolute thresholds of the P-channel may have been lowered by spatial summation (Verrillo 1966, 1985), although the effect of spatial summation on relative difference thresholds is not known. Gescheider *et al*. usually employed a small number of highly trained subjects with a wide age range and both genders, whereas the current study had a larger number of untrained subjects with smaller age range and the same gender. While there is some evidence that aging does not affect relative difference thresholds of the P channel other than at sensation levels slightly above the absolute threshold (Gescheider *et al*. 1994), effects of gender and training cannot be excluded. Gescheider *et al*. (2009) report reductions of up to 50% in relative difference thresholds when subjects were trained for a period of 23 days.

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

The duration of the vibration stimuli also differed between the present study and the Gescheider *et al*. studies. Similar to spatial summation, temporal summation of the P channel also reduces absolute thresholds (Verrillo 1965). With 250-Hz vibration varying from 10 to 700 ms in duration applied to the thenar eminence of the hand, Gescheider *et al.* (1996) investigated the effects of stimulus duration on relative difference thresholds using both a gated-pedestal method (i.e. with a pause between the two measurement intervals) and a continuous pedestal method (with no pause between the measurement intervals). They found that the relative difference thresholds were not affected by duration when the gated pedestal method was employed, but that relative difference thresholds decreased with increasing stimulus duration when the continuous pedestal method was employed. The present study also used the gated-pedestal method, but had stimulus durations of 2000 ms, much longer than the maximum duration used by Gescheider *et al*. The longer stimulus duration in the current experiment may have contributed to saturation of the P channel at lower levels. The frequencies of vibration used in the two studies (250 Hz by Gescheider *et al*. and 125 Hz in the present study) both excite the P channel over a wide range of magnitudes, but there may be differences due to the use of the different frequencies.

6.5. CONCLUSION

The findings of Experiment III are in some ways similar to those from Experiment II.

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

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

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

CHAPTER 7: MASKED DIFFERENCE THRESHOLDS

7.1. INTRODUCTION

As was the case for the three earlier experiments, one main aspect of the thesis and the findings so far remained to be the extent of involvement of somatosensory channel mediation in the perception of differences. In order to assist with the identification of the channels involved the process, a masking experiment was considered, which was also likely to provide a better understanding of the neurological and cognitive aspects of the difference thresholds.

The effect of masking on difference thresholds is not well understood, but it was anticipated that by investigating the extent to which difference thresholds at one frequency were affected by masking produced by vibration at another frequency, it would be possible to improve understanding of the channels responsible for detecting difference thresholds at different vibration magnitudes.

There have been earlier studies of absolute thresholds and difference thresholds for vibration applied to the hand, and some studies of the masking of absolute thresholds for hand-transmitted vibration (for a summary, see Chapter 2). However, there have been few studies of the effect of masking on difference thresholds. Craig (1972) and Gescheider *et al*. (1994a) found the relative difference threshold was increased by the addition of a masking vibration.

Craig (1972) used 200-millisecond sinusoidal 160-Hz vibration applied to the fingertip through a 6-mm diameter circular contactor to obtain masked difference thresholds at three sensation levels (at 15, 20, and 30 dB above the absolute threshold of perception) with and without a broadband vibration masker at four magnitudes (14, 21, 28, and 35 dB SL). The non-masked relative difference thresholds were constant, at about 0.16 at the four vibration magnitudes. Craig found that, in general, the addition of a background vibration increased the relative difference threshold and concluded 'for vibratory stimuli, plotting [difference thresholds] as a function of decibels above threshold, either masked or quiet threshold, yields a single function'.

Gescheider *et al*. (1994a) measured masked difference thresholds employing 700-ms 250-Hz sinusoidal vibration. The stimuli were applied to the thenar eminence of the hand through a circular contactor with an area of 2.9 cm^2. They found that ‘adding the masking stimulus at a particular test stimulus intensity tends to increase the size of the [difference threshold]’. By matching the levels of the non-masked and masked test stimuli, they concluded that the relative intensity difference thresholds are ‘independent of the level of masking noise provided the subjective magnitudes of the stimuli are equal’.

The studies of Craig (1972) and Gescheider *et al*. (1994a) suggest that the addition of a masking stimulus tends to increase the difference thresholds (ΔI), possibly due to the total stimulus intensity (I) being increased by the addition of the masker vibration. Both studies also suggest that when the subjective magnitudes of the reference stimuli are equal (i.e., when the reference stimulus has the same sensation level, above either the masked or the unmasked threshold), the relative difference thresholds remain the same.

The objective of the present experiment was to obtain the masked difference thresholds for sinusoidal hand-transmitted vibration at two magnitudes of a reference vibration. The masker was narrowband vibration centred on 16 Hz and the reference vibration was sinusoidal at 125 Hz. Low-magnitudes of the 16-Hz masker were expected to excite the non-Pacinian I (NPI) channel but not the Pacinian (P) channel. Low magnitudes of the 125-Hz vibration were expected to excite the P channel but not the NPI channel. As the magnitude of the masker vibration increased, it was expected that the vibration would be more likely to be detected by the P channel (Bolanowski *et al.,* 1988; Gescheider *et al.,* 2001). Consequently, the masked 125-Hz difference thresholds (ΔI), were expected to increase when the 16-Hz masker increased in magnitude sufficiently to increase the sensation magnitude of the reference vibration (intensity above the threshold of the P channel). The increase was expected to be observed when the magnitude of the 16-Hz masker was high enough to stimulate the somatosensory channel detecting the 125-Hz vibration (i.e., the P channel for the 9 dB sensation level reference vibration, and either the P or one of the NP channels for the 21 dB SL reference vibration).

7.2. METHOD

The experiment involved twelve sessions per subject, with each session providing two absolute thresholds and six masked difference thresholds, in addition to one difference threshold during training. In six sessions, the magnitude of the sinusoidal 125-Hz reference vibration was at 9 dB sensation level, and in the other six it was at 21 dB SL.

At the start of each session, the absolute threshold of the subject was measured for the 125-Hz sinusoidal vibration and also for the 1/3rd octave narrowband masker centred on 16 Hz. These thresholds were then used to calculate the required magnitudes for the 125-Hz stimuli and 16-Hz maskers during the masked difference threshold measurements. All masked difference thresholds in a session were obtained with the same reference vibration magnitude (either 9 or 21 dB SL). Before the start of tests in each session, the subjects were given training in masked difference threshold detection. The masked difference threshold measurements at different magnitudes within a session were presented according to a latin-square design.

Four right-handed, young, healthy male subjects with no previous experience of relative difference threshold measurement took part in the experiment. The subjects were aged 21, 23, 24 and 27 years with statures of 165, 177, 178 and 173 cm and weights of 51, 80, 88 and 80 kg. All subjects were either members of staff or students at the University of Southampton. The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

Subjects were given written instructions before the tests (See Appendix A). The skin temperature was measured at the fingertips before the experiment to avoid temperature-related shifts in threshold (Verrillo and Bolanowski, 1986). All subjects had right-hand skin temperatures greater than 30 degrees Celsius before the testing started. Auditory masking (white noise at 65 dBA) was presented via headphones during the threshold determinations.

7.2.1. Apparatus

The experiment was conducted using a MB Dynamics model Red electro-dynamic vibrator. The vertical vibration was applied through a rigid metal handle with a circular cross-section (30-mm diameter) coupled rigidly to the vibrator. The subjects sat on a padded saddle and gripped the handle with their right hand. The grip was instructed to be comfortable and of constant force (Figure 7.1). The left hand gripped an identical handle but it was not exposed to vibration. The feet of subjects were supported by a frame fixed to the ground.

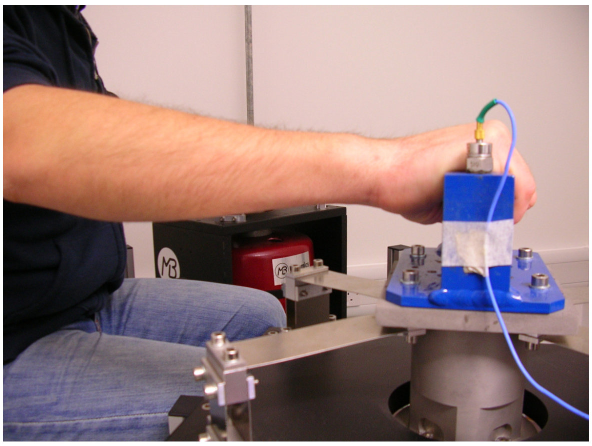


Figure 7.1 Handle-grasping posture.

The vibration was produced and measured using a specially written programme in the *HVLab* data acquisition system (version 3.81). The signals were generated at 5000 samples per second and passed through a 300-Hz low-pass filter. An MB Dynamics Model SL 500VCF power amplifier amplified the drive signal to the vibrator. Vibration was measured on the vibrating handle using a DJ Birchall (A 20/T) piezo-electric accelerometer. A diagram of the experimental setup is shown in Figure 7.2.

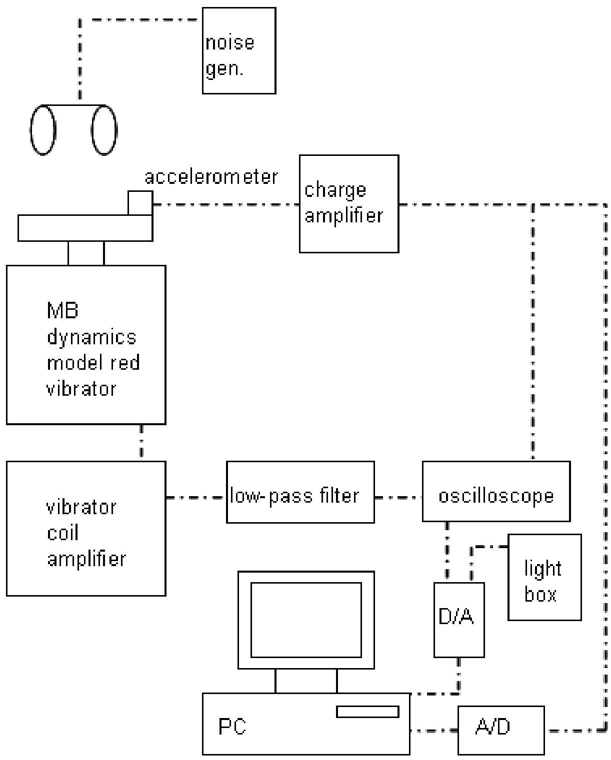


Figure 7.2. Set-up used in Experiment IV.

Mathworks MATLAB software (version 7.0.4.365.R14) was used to analyse the results.

7.2.2. Psychophysical method

Difference thresholds for two magnitudes (9 dB SL and 21 dB SL) of the 125-Hz reference vibration were measured in the presence of six masker magnitudes (no masker, 0, 6, 12, 18, 24 dB SL). The magnitudes of the reference vibration and the masker vibration were calculated after the determination of absolute thresholds of each subject.

The up-down-transformed-response (UDTR) method was used to obtain both the absolute perception thresholds and the masked difference thresholds (Wetherill and Levitt, 1965). The UDTR method is a variant of the method of limits, where the magnitude of the test vibration is increased or decreased depending on the responses of the subject. For the measurement of both absolute thresholds and difference thresholds, the stimuli were presented with a two-interval forced-choice procedure. A red light was used to indicate the intervals during which stimuli were presented. Responses of the subjects were tracked using the three-down-one-up rule. When a subject gave three consecutive correct answers, the magnitude of the test vibration was reduced by one step, and when a subject gave an incorrect answer, the magnitude of the test vibration was increased by one step. Each vibration lasted 1 second with 0.1 second rise and decay times.

When determining absolute thresholds, only one of the two intervals contained the test vibration: subjects were asked to identify the interval during which the vibration stimulus was present. The step size was 1 dB (i.e., 12.2%).

When determining difference thresholds, both intervals contained a vibration and the subject was asked to identify the interval that contained the stronger vibration. The test vibration was always stronger than the reference vibration, with a step size of 0.333 dB (i.e., 3.91%).

At the beginning of each masked difference threshold trial, the 1-s test vibration was presented without the masker. This 'non-masked interval' was followed by a 0.5-s pause and then a 4-s period of masker vibration with 0.1-s rise and fall times. The test and reference vibration (both 1-s in duration) were presented during this masker vibration, separated by 1 s. The first interval started 0.5-s after the onset of the masker, and the second interval stopped 0.5 s before the masker stopped (Figure 7.3). The order of presentation of the test vibration and the reference vibration was random.

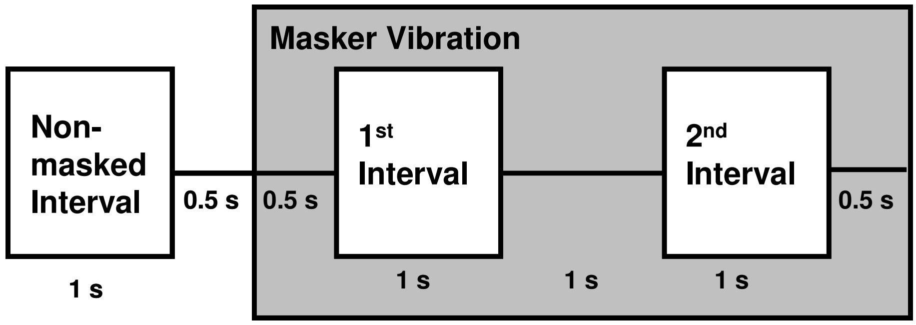


Figure 7.3. Masked difference threshold measurement intervals.

Both the absolute thresholds and the difference thresholds were calculated from the reversal points (i.e., the trials at which the direction of change of magnitude of the test vibration was reversed). In order to obtain thresholds, six reversals were obtained and the average of the last four was taken after discarding the first two.

When calculating the relative difference threshold, it was not possible to use the acceleration measured during the reference interval, because this included the masker vibration. Instead, the magnitude of the unmasked test vibration was measured during the non-masked interval and later used to calculate the magnitude of the reference vibration during each trial (R_i). The assumed magnitude of the reference vibration was the average magnitude of the reference vibration in all trials.

$$R_c = \frac{\sum_{i=1}^{N=T} R_i}{T} \qquad (7.1)$$

where T is the number of trials to obtain a threshold (i.e. the number of measurements).

A masked difference threshold was then obtained from:

$$\text{difference threshold} = \frac{\sum_{i=3}^{N=6}(M_i - R_c)}{(N-2)} \qquad (7.2)$$

where N is the number of reversals (N=6), and M_i is the r.m.s. acceleration magnitude of the test vibration measured in the non-masked interval at the beginning of a trial.

To determine a relative difference threshold, the absolute value of the difference threshold for that stimulus was divided by the r.m.s. acceleration magnitude of the calculated reference vibration, R_c:

$$\text{relative difference threshold} = \sum_{i=3}^{N=6}\left(\frac{M_i - R_c}{R_c \cdot (N-2)}\right) \qquad (7.3)$$

7.3. RESULTS

7.3.1. Absolute thresholds

The median absolute thresholds for the third-octave masker vibration centred on 16 Hz were 0.146, 0.149, 0.151 and 0.237 ms^{-2} r.m.s. The median absolute thresholds for the unmasked 125-Hz sinusoidal reference vibration were 0.015, 0.016, 0.017 and 0.022 ms^{-2} r.m.s. These thresholds are the medians of the four subjects' median absolute thresholds measured in the 12 sessions).

Absolute thresholds for the 16 Hz and 125 Hz vibrations are shown in Figures 7.4 and 7.5.

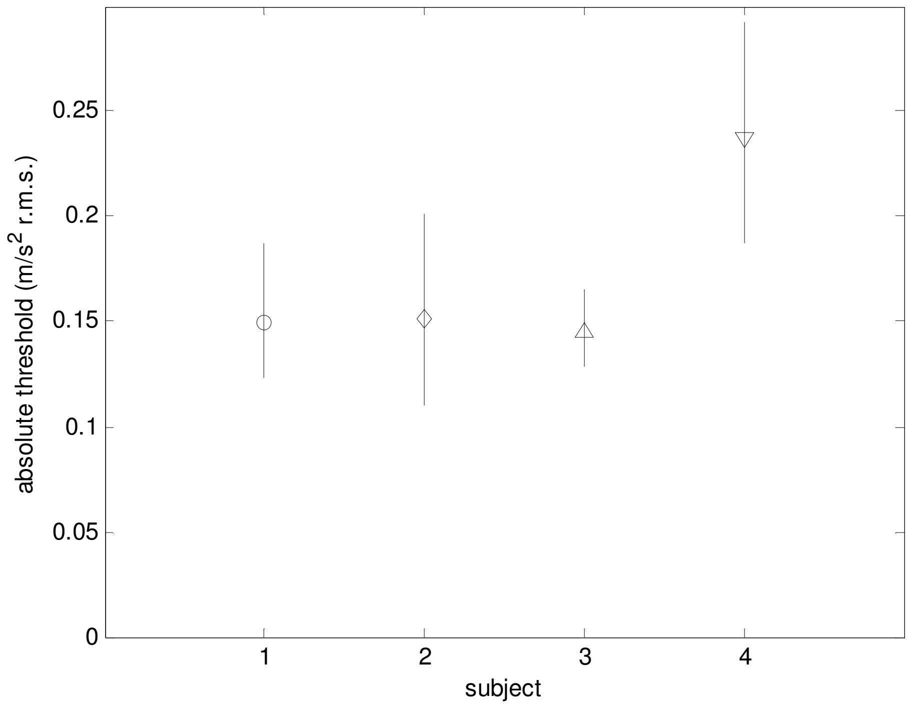


Figure 7.4. Median absolute thresholds and interquartile ranges of all four subjects (medians of six measurements) with 16-Hz centred third-octave vibration.

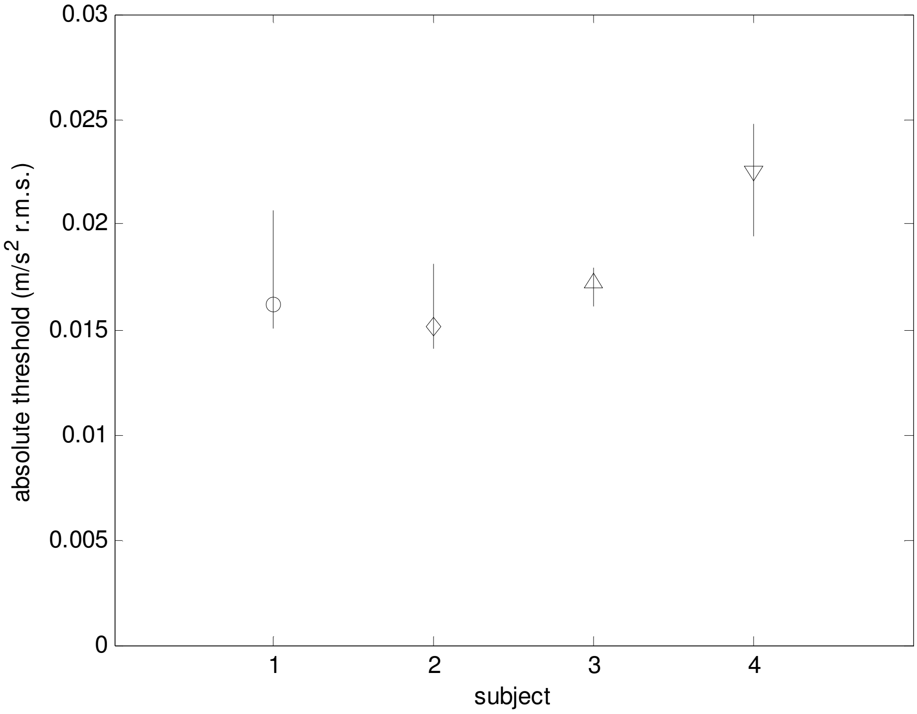


Figure 7.5. Median absolute thresholds and interquartile ranges of all four subjects (medians of six measurements) with 125-Hz sinusoidal vibration.

7.3.2. Effect of masking on difference thresholds

The median relative difference thresholds, obtained from the six measurements at each masker magnitude for each subject, are shown in Figure 7.6.

The unmasked relative difference thresholds of the 125-Hz reference vibration were similar at both magnitudes: 0.32 at 9 dB SL and 0.31 at 21 dB SL (medians of the median thresholds of the four subjects).

At 9 dB SL, the masked relative difference thresholds varied significantly with masker magnitude for all four subjects ($p \leq 0.0175$; Friedman). At 21 dB SL, the masked relative difference thresholds of two subjects varied significantly with masker magnitude (subject 1, $p = 0.0486$; subject 2, $p = 0.0452$, Friedman).

At 9 dB SL, the masked relative difference thresholds of all subjects were greatest with the greatest masker (i.e., 24 dB SL masker). All four subjects had greater masked relative difference thresholds with the 18 dB SL masker than the 12 dB SL masker. The relative difference thresholds for the unmasked and the masked reference vibration were similar as the masker magnitude increased up to 12 dB SL for three of the subjects. However, for one subject the relative difference threshold consistently increased as the masker magnitude increased from 0 dB SL to 24 dB SL (Figure 7.6).

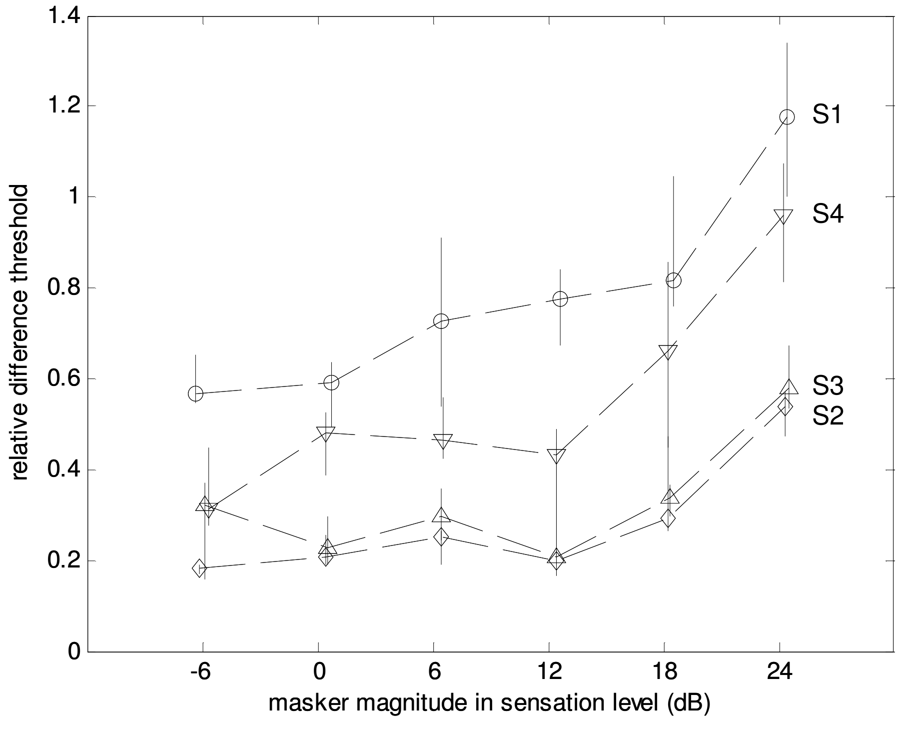


Figure 7.6. Median relative difference thresholds for all four subjects (medians of six measurements and interquartile ranges) at 9 dB SL reference magnitude.

At 21 dB SL, the trends are less clear (Figure 7.7). For three of the four subjects, the relative difference thresholds were greater with 24 dB SL masking than with less masking. For Subject 1, the masked relative difference thresholds increased consistently as the masker magnitude increased from 0 dB SL to 24 dB SL. Overall, the masked relative difference threshold curves at 21 dB SL are flatter than those obtained at 9 dB SL.

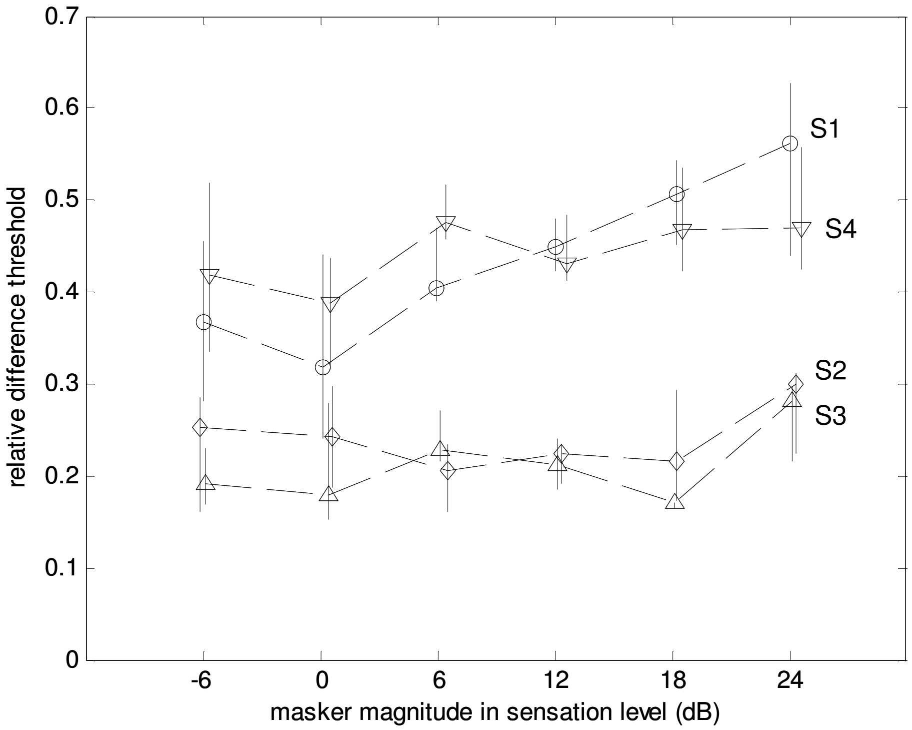


Figure 7.7. Relative difference thresholds for all four subjects (medians of six measurements and interquartile ranges) at 21 dB SL reference magnitude.

As with the 9 dB SL reference magnitude case, the relative difference thresholds varied greatly between the four subjects.

7.3.3. Intra-subject variability of difference thresholds

Intra-subject variability, in terms of the ratio of the inter-quartile range of the six relative difference threshold measurements to the median relative difference threshold at that masker magnitude is shown in Tables 7.1 and 7.2.

Table 7.1. Ratio of inter-quartile ranges to median relative difference thresholds: 9 dB SL reference.

	Subject 1	Subject 2	Subject 3	Subject 4
No masker	0.186	0.125	0.666	0.551
0 dB SL	0.243	0.325	0.466	0.296
6 dB SL	0.511	0.082	0.573	0.310
12 dB SL	0.217	1.339	1.446	0.171
18 dB SL	0.352	0.709	0.209	0.622
24 dB SL	0.290	0.182	0.239	0.275

Table 7.2. Ratio of inter-quartile ranges to median relative difference thresholds: 21 dB SL reference.

	Subject 1	Subject 2	Subject 3	Subject 4
No masker	0.477	0.493	0.319	0.467
0 dB SL	0.634	0.449	0.714	0.308
6 dB SL	0.194	0.363	0.246	0.124
12 dB SL	0.131	0.191	0.255	0.167
18 dB SL	0.185	0.556	0.036	0.206
24 dB SL	0.332	0.288	0.296	0.284

The intra-subject variability tended to be lower for the 21 dB SL reference.

7.4. DISCUSSION

7.4.1. Effect of masking on difference thresholds

For the 9 dB SL relative difference thresholds (Figure 7.6), increases in the masker magnitude seem to have had little effect below a masker magnitude of 12 dB SL. This is consistent with the prediction that the masker and the reference stimuli would initially be detected by different somatosensory channels, so that increases in masker magnitude would not affect the relative difference thresholds until the masker (initially only detected by the NPI channel) reached a sufficiently high magnitude (i.e., the 'cross-talk point') to be detected by the channel mediating the relative difference threshold (i.e., the P channel). This is because masking occurs only if the masker vibration and the test vibration excite the same channel (Gescheider *et al.*, 1982, 1985). When the masker magnitude was increased (i.e., to 18 or 24 dB SL), the relative difference thresholds were greater, consistent with the masker exciting the channel determining the difference threshold.

The effect of the masker is not seen as clearly in the 21 dB SL reference curves (Figure 7.7). While some studies suggest that 21 dB SL could be sufficiently high to excite more than one somatosensory channel at 125 Hz (Bolanowski *et al.,* 1988; Forta *et al.*, 2007), the median masked relative difference thresholds obtained in this study indicate that the relative difference thresholds are still mediated by the same channel responsible for the thresholds observed with the 9 dB SL reference. Three observations favour this suggestion:

(i) The non-masked difference thresholds are similar with the two reference magnitudes (about 0.3).

(ii) The 16-Hz centred noise masker had little effect on the relative difference thresholds of either condition below 12 dB SL masker, except for one subject.

(iii) The 21 dB SL curves also exhibit higher relative difference thresholds with the 24 dB SL masker (except for one subject), but the difference is not as pronounced as for 9 dB SL.

The milder increase in the 21 dB SL relative difference thresholds could be due to the 1.0 slope of the simultaneous masking curve (Gescheider *et al.*, 1982; Hamer, 1979), once the cross-talk point is reached. The excitation carried over to the P channel from the masker would be the same for both reference magnitudes for a given masker magnitude. Since the 125-Hz reference exciting the P channel in the 21 dB SL condition would be about four times the magnitude of the 125-Hz reference exciting the same channel in the 9 dB SL condition, the addition of an equal amount of excitation to both channels from the masker would have a weaker masking effect on the 21 dB SL reference.

The observed increases in the relative difference thresholds can be attributed to the method of quantifying the reference excitation and the relative difference thresholds (Equations 7.1 and 7.3), which assume that the P excitation is constant and comes exclusively from the 125-Hz reference vibration. When the masker is sufficient in magnitude to excite the P channel, the masker increases the total excitation (assumed here to be solely due the magnitude of the reference, I) to a greater amount ($I + I_{masker}$), where I_{masker} is the effect of the masker above the threshold of the P channel. If the channel conforms to Weber's Law (i.e. $\Delta I \,/\, I = constant$), as the total excitation increases (to $I + I_{masker}$) the absolute difference, ΔI, must increase – as seen in the present results. If it were possible to measure the P excitation directly, and the channel behaved in a perfectly Weberian way, the measured 'true' relative difference thresholds (Weber fractions) would have remained constant. This conclusion is consistent with that of Craig (1972) and Gescheider *et al.* (1994a).

7.4.2. Intra-subject variability of difference thresholds

There are no known previous reports of the repeatability of difference threshold measurements. The greater variability at the 9 dB SL reference magnitude than at the 21 dB SL reference magnitude might be due to 9 dB being close to the absolute threshold and relatively sensitive to random effects.

7.5. CONCLUSIONS

Intra-subject variability of the masked and unmasked relative difference thresholds were high (the ratios of the inter-quartile ranges to the relative difference thresholds were 0.082 to 1.446 at 9 dB SL and 0.036 to 0.714 at 21 dB SL).

With 125-Hz sinusoidal vibration, both 9 dB SL and 21 dB SL magnitudes had median unmasked relative difference thresholds of about 0.3, suggesting that the same channel (probably the Pacinian channel) was responsible for the determination of the relative difference thresholds for most subjects.

The addition of a 16-Hz third-octave masker did not have a clear effect on the relative difference thresholds until the masker magnitude reached about 12 dB SL, but masker magnitudes greater than 12 dB SL increased the relative difference thresholds for 9 dB SL reference magnitude.

The findings are consistent with the Pacinian channel following Weber's Law, causing the relative difference thresholds measured in this study to: (a) be similar at the two reference magnitudes when not masked, and (b) rise when the non-Pacinian masker was of sufficient magnitude to excite the Pacinian channel.

CHAPTER 8: DIFFERENCE THRESHOLDS WITH LOCAL VIBRATION

8.1. INTRODUCTION

The first three experiments of this thesis raised questions about the roles of the somatosensory channels in the perception of differences in vibration magnitude. Relevant findings came to light in the fourth experiment (Chapter 8 and Forta, 2008), but the scope for a study concentrating on the role of somatosensory channels remained, so a fifth experiment was designed to focus on channel responses.

The majority of studies on difference thresholds in the literature that have discussed their findings in terms of somatosensory channels were conducted using localised excitation of the hand. Conducting the fifth experiment of the current thesis using a similar design was therefore considered ideal, since this would allow:

i. more accurate comparisons with earlier independent studies
ii. better isolation of channel effects
iii. the gathering of a set of results obtained with an alternative method which can then be compared to the results from the earlier experiments of the thesis and add to the discussion on channel effects.

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

The receptors of the Pacinian channel are Pacinian nerve endings that are found in both glabrous and hairy skin, and in some other tissues such as tendons. Receptors of the non-Pacinian I channel are the Meissner nerve endings that are found in glabrous skin. Absolute thresholds for the perception of vibration at the volar forearm and the thenar eminence have been found to differ by 11 dB at 25 Hz and about 20 dB at 125 Hz, when measured using a contactor 1.3 cm^2 in area, with the difference attributed to differences in receptor densities at the two sites (Verrillo, 1966).

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

Some studies have found that contrary to Weber's Law the magnitude of the vibration has affected vibration intensity relative difference thresholds. With sinusoidal vibration applied by a 2.9 cm^2 contactor to the thenar eminence of the hand, Gescheider *et al.* (1990) found reductions in difference thresholds with increasing vibration magnitude, from about 0.26 at 4 dB SL to 0.12 at 40 dB SL (where SL is the sensation level – the level above the absolute threshold of perception of the subject), with similar relative difference thresholds at 25 Hz and 250 Hz (differing by less than about 0.05). Gescheider *et al.* (1996a) found that relative difference thresholds for 250 Hz sinusoidal vibration applied to the thenar eminence decreased from about 0.26 at 4 dB SL to about 0.16 at 36 dB SL. A reduction in the relative difference thresholds with increasing vibration magnitude was also reported in Gescheider *et al.* (1997a) with skin temperatures of 20, 30, and 40 ^{o}C. At all three temperatures the relative difference thresholds reduced from about 0.23 at 4 dB SL to 0.13 at 42 dB SL.

Using a gripping posture and 125-Hz sinusoidal vibration, relative difference thresholds increased as the vibration magnitude increased from 12 dB SL to 36 dB SL, but there was no significant effect of vibration magnitude with 16-Hz vibration (Chapter 5, also Forta, 2007).

It is not clear from the literature whether difference thresholds depend on the channel mediating the sensation of vibration. The objective of the experiment described here was to investigate the dependence of intensity difference thresholds for sinusoidal vibration on the somatosensory channel mediating the threshold. The vibration frequencies of 10 Hz and 125 Hz were selected so as to excite the non-Pacinian I channel (with 10 Hz vibration) and the Pacinian channel (with 125 Hz vibration) when the vibration was 10 dB above the absolute threshold. It was hypothesised that the relative difference thresholds (i.e., Weber fractions) would differ between the NPI and P channel. It was also hypothesised that absolute thresholds would be higher at the volar forearm than at the thenar eminence due to the lower density of the mechanoreceptors at the forearm.

8.2. METHOD

8.2.1. Apparatus

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

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

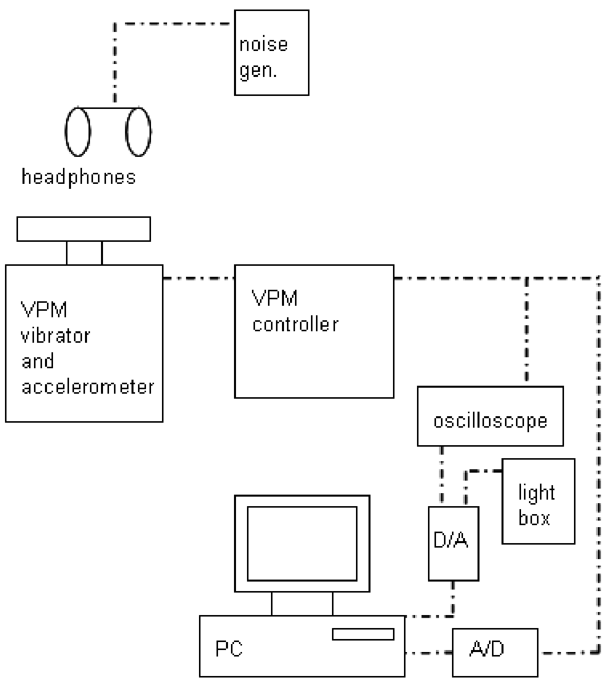


Figure 8.1. The experimental set-up.

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

8.2.2. Subjects and postures

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

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

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

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

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

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

With the arm resting on a support on one table, the subject's thenar eminence made contact with the VPM resting on a different table. The fingers rested on a foam surface on the same table as the VPM. For the tests at the forearm, the arrangement was the same except the arm rest supported the arm nearer to the elbow. Subjects were instructed to maintain the same posture throughout the experiment (Figure 8.2).

Figure 8.2. Posture and set-up used in the experiment.

8.2.3. Sessions

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

The absolute thresholds obtained in the first and third sessions were used to calculate the reference magnitudes at which difference thresholds were obtained in the second and fourth sessions. At both frequencies, difference thresholds were measured at two sensation levels at the thenar eminence and one sensation level at the volar forearm. Six difference thresholds were obtained for one contactor in one session (four on the thenar eminence and two on the volar forearm) (Table 8.1). In order to keep the waveform distortion to a minimum (about 5%) at all frequencies and magnitudes, the sensation levels varied with contact area, contact location, and vibration frequency. Some subjects had high absolute thresholds in some conditions, leading to higher absolute magnitudes.

Table 8.1. Conditions for difference threshold measurements.

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

8.2.4. Psychophysical methods and vibration stimuli

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

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

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

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

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

A difference threshold was calculated using:

$$\text{difference threshold} = \sum_{i=3}^{N=6}\left(\frac{(M_i - R_i)}{(N-2)}\right) \qquad (8.1)$$

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

To determine a relative difference threshold, the absolute value of the difference threshold for that stimulus was divided by the r.m.s. acceleration magnitude of the reference vibration, R_i:

$$\text{relative difference threshold} = \sum_{i=3}^{N=6}\left(\frac{M_i - R_i}{R_i \cdot (N-2)}\right) \qquad (8.2)$$

8.2.5. Statistical methods

Mathworks Inc. MATLAB (R14) software with Statistics Toolbox, was used to calculate the thresholds and perform the subsequent statistical analysis of the results. Non-parametric tests (Friedman test and the Wilcoxon matched-pairs signed ranks test for two-related samples) were employed in the statistical analysis.

8.3. RESULTS

8.3.1. Absolute thresholds

For both frequencies and both locations, absolute thresholds measured with the 1-mm diameter contactor were significantly greater than absolute thresholds measured with the 10-mm diameter contactor ($p < 0.001$, Wilcoxon; Figure 8.3).

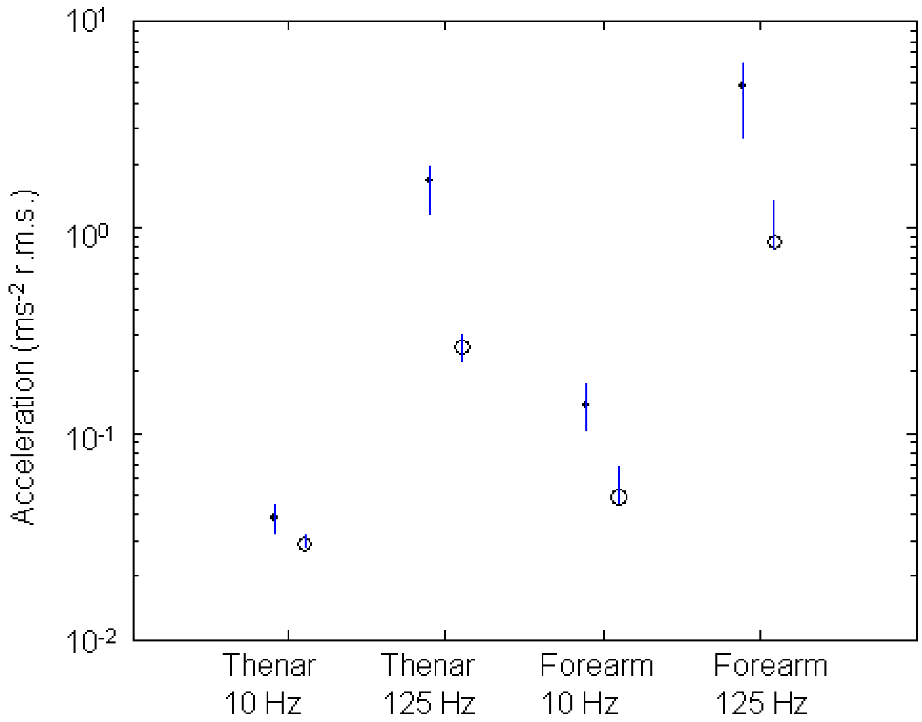


Figure 8.3. Absolute thresholds (medians of 12 subjects) and interquartile ranges at the thenar eminence of the hand and at the volar forearm: ● 1-mm diameter contactor; o 10-mm contactor.

For both test frequencies, absolute thresholds at the volar forearm were significantly greater than absolute thresholds measured at the thenar eminence on the hand ($p < 0.0005$, Wilcoxon).

Within each combination of frequency and location, absolute thresholds with the 1-mm and 10-mm contactors were only significantly correlated with each other on the volar forearm at 125 Hz ($p = 0.0145$, Spearman).

With the 1-mm contactor, thresholds on the thenar eminence at 10 Hz were correlated with the thresholds on the volar forearm at 125 Hz ($p = 0.010$, Spearman). Other comparisons across test conditions were not significantly correlated with each other ($p > 0.061$, Spearman).

With the 10-mm contactor, there were no significant correlations across the test conditions ($p > 0.391$, Spearman).

Correlations between 1-mm thresholds and 10-mm thresholds, obtained at different locations and frequencies, were not significant except for 1-mm thresholds on the thenar eminence at 10 Hz being correlated with the 10-mm thresholds on the volar forearm at 125 Hz ($p = 0.0032$, Spearman).

8.3.2. Difference thresholds

Median relative difference thresholds obtained from the 12 subjects are given in Figure 8.4.

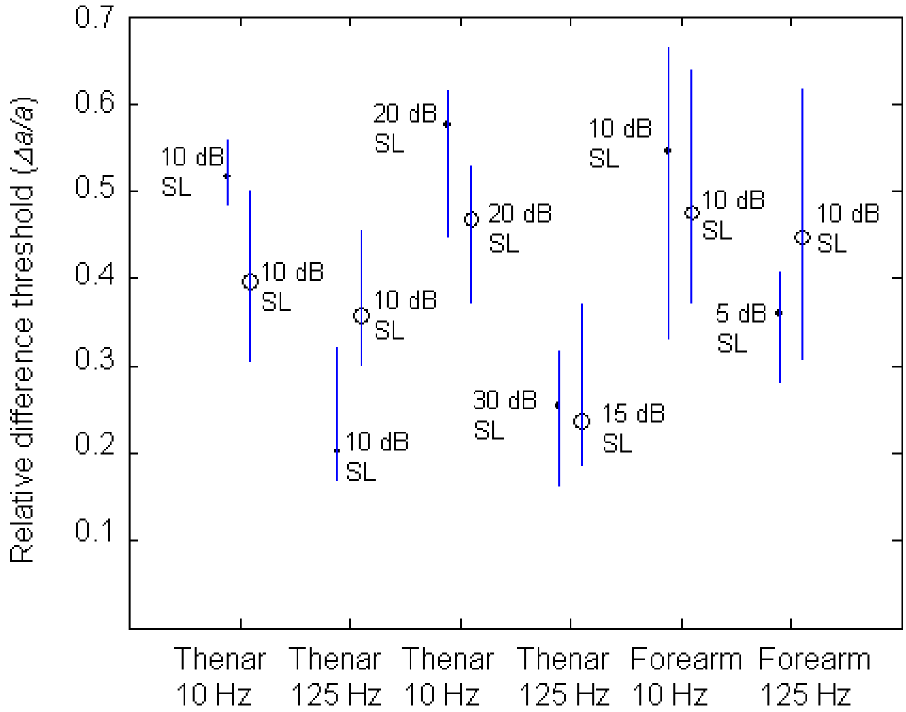


Figure 8.4. Relative difference thresholds (medians of 12 subjects): ● 1-mm diameter contactor; o 10-mm contactor. Irregular sensation levels shown next to median thresholds.

Comparison of the relative difference thresholds likely to arise from the response of only the NPI channel (1-mm contactor; thenar eminence, 10 Hz, 10 dB SL) with the relative difference thresholds likely to be from the response of only the P channel (10-mm contactor: thenar eminence, 125 Hz, 10 dB SL) revealed lower relative difference thresholds for the P channel (median 0.36) than the NPI channel (median value was 0.52), with the difference marginally not statistically significant (p = 0.064, Wilcoxon). Results of statistical tests for all conditions are reported in Table 8.2.

Table 8.2. Significance of differences between relative difference thresholds (*p*-values for Wilcoxon tests): * $p < 0.05$, ** $p < 0.01$. TE = thenar eminence; VF = volar fore-arm.

				Thenar eminence (TE)				**Volar fore-arm (VF)**	
				1 mm contactor					
				10 dB	**10 dB**	**20 dB**	**30 dB**	**10 dB**	**5 dB**
Contact	**Location**	**Level**	**Frequency**	**10 Hz**	**125 Hz**	**10 Hz**	**125 Hz**	**10 Hz**	**125 Hz**
1.0 mm	**TE**	**10 dB**	**10 Hz**	--	0.0015**	1	0.0015**	0.9097	0.0342*
		10 dB	**125 Hz**	0.0015**	--	0.0024**	0.9097	0.0024**	0.1294
		20 dB	**10 Hz**	1	0.0024**	--	0.0034**	0.9097	0.1099
		30 dB	**125 Hz**	0.0015**	0.9097	0.0034**	--	0.0015**	0.1099
	VF	**10 dB**	**10 Hz**	0.9097	0.0024**	0.9097	0.0015**	--	0.0923
		5 dB	**125 Hz**	0.0342*	0.1294	0.1099	0.1099	0.0923	--
10 mm	**TE**	**10 dB**	**10 Hz**	0.0269*	0.0005**	0.064	0.064	0.1294	0.4238
		10 dB	**125 Hz**	0.064	0.0049**	0.1294	0.0093**	0.2334	0.8501
		20 dB	**10 Hz**	0.064	0.0034**	0.2036	0.0093**	0.3804	0.2036
		15 dB	**125 Hz**	0.0010**	0.3013	0.0049**	0.791	0.0049**	0.1514
	VF	**10 dB**	**10 Hz**	0.5186	0.0010**	0.6221	0.0093**	0.8501	0.1099
		5 dB	**125 Hz**	0.3804	0.0093**	0.3804	0.0161*	0.6773	0.4697
				Thenar eminence (TE)				**Volar fore-arm (VF)**	
				10 mm contactor					
				10 dB	**10 dB**	**20 dB**	**15 dB**	**10 dB**	**10 dB**
				10 Hz	**125 Hz**	**10 Hz**	**125 Hz**	**10 Hz**	**125 Hz**
1.0 mm	**TE**	**10 dB**	**10 Hz**	0.0269*	0.064	0.064	0.0010**	0.5186	0.3804
		10 dB	**125 Hz**	0.0005**	0.0049**	0.0034**	0.3013	0.0010**	0.0093**
		20 dB	**10 Hz**	0.064	0.1294	0.2036	0.0049**	0.6221	0.3804
		30 dB	**125 Hz**	0.064	0.0093**	0.0093**	0.791	0.0093**	0.0161*
	VF	**10 dB**	**10 Hz**	0.1294	0.2334	0.3804	0.0049**	0.8501	0.6773
		10 dB	**125 Hz**	0.4238	0.8501	0.2036	0.1514	0.1099	0.4697
10 mm	**TE**	**10 dB**	**10 Hz**	--	0.8501	0.2036	0.0093**	0.1099	0.6221
		10 dB	**125 Hz**	0.8501	--	0.3804	0.0425*	0.0342*	0.4238
		20 dB	**10 Hz**	0.2036	0.3804	--	0.0024**	0.4697	0.791
		15 dB	**125 Hz**	0.0093**	0.0425*	0.0024**	--	0.0015**	0.064
	VF	**10 dB**	**10 Hz**	0.1099	0.0342*	0.4697	0.0015**	--	0.5186
		10 dB	**125 Hz**	0.6221	0.4238	0.791	0.064	0.5186	--

With the 1-mm contactor, relative difference thresholds were significantly greater at 10 Hz than at 125 Hz ($p < 0.035$, Wilcoxon), except on the thenar eminence for 10 Hz at 20 dB SL and on the volar forearm for 125 Hz at 5 dB SL.

With the 10-mm contactor, relative difference thresholds were lower on the thenar eminence with 125 Hz at 15 dB SL than in all other conditions ($p < 0.043$, Wilcoxon), except when compared with thresholds at the volar forearm with 125 Hz at 5 dB SL. Relative difference thresholds were lower on the thenar eminence with 125 Hz at 10 dB SL than relative difference thresholds on the volar forearm with 10 Hz at 10 dB SL ($p = 0.0015$, Wilcoxon).

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

8.4. DISCUSSION

8.4.1. Absolute thresholds

Absolute thresholds at the thenar eminence were similar to those reported by Bolanowski *et al*. (1988). With 10 Hz vibration and a 2.9 cm^2 contactor, Bolanowski *et al*. reported median absolute thresholds of 20 dB (in peak displacement re 1 micrometer) compared with 20.3 dB in the current study with the 0.8 cm^2 contactor (10 mm diameter) and 22.3 dB with the 0.008 cm^2 contactor (1 mm diameter). With 125 Hz vibration, and also with a 2.9 cm^2 contactor, Bolanowski *et al*. (1988) reported thresholds of about -10 dB compared to -4.4 dB with the 0.8 cm^2 contactor and 11.5 dB with the 0.008 cm^2 contactor in the present study.

The differences between the results of the two studies are likely to be partially due to the different sizes of the contactors. With 125-Hz vibration applied to the thenar eminence, the threshold is mediated by the P channel, which has a spatial summation capability (for spatial summation, see Section 2.3.3, also Verrillo, 1963, 1965, 1966, 1985; Morioka and Griffin, 2005). Assuming a threshold reduction of 3 dB per doubling of area (Verrillo, 1963), and using thresholds from Bolanowski *et al*. (1988), the large contactor in this experiment would be expected to produce a threshold of -6.4 dB, which is closer to the measured threshold of -4.4 dB, than the threshold of -10 dB Bolanowski *et al.* obtained with the 2.9 cm^2 contactor in their study. The psychophysical method used in the present study estimated the thresholds for 79.4% correct detection on the psychometric function compared to 75% in the study by Bolanowski *et al*. (1988), so were likely to produce slightly higher thresholds. There were also differences between the subject populations: 12 untrained young males in the present study and five trained subjects of both genders and a wider age range in Bolanowski *et al*. (1988). The different durations of the vibration stimuli (1000 ms in the current study and 700 ms by Bolanowski *et al*.) is unlikely to have caused the higher thresholds in the current study because the temporal summation of the P channel would tend to reduce thresholds.

With 125-Hz vibration in the current study, the 10-mm contactor produced absolute thresholds about 16 dB lower than the 1-mm contactor, consistent with spatial summation in the P channel. With 10-Hz vibration the 10-mm contactor produced absolute thresholds about 2.5 dB lower than the 1-mm contactor, possibly a result of there being a lower chance of the 1-mm contactor being placed in the field of a sensitive mechanoreceptor.

Absolute thresholds at the volar forearm were greater than thresholds at the thenar eminence, likely to be due to a higher density of mechanoreceptors in the glabrous skin of the thenar eminence than the hairy skin of the volar forearm. With the 1 mm contactor, the absolute thresholds were about 11 dB greater at the volar forearm at 10 Hz, and about 9.2 dB greater at 125 Hz. With the 10 mm contactor, the volar forearm thresholds were greater by 4.6 dB at 10 Hz and 10.1 dB at 125 Hz. Differences between the thresholds from the two locations are lower than those found by Verrillo (1966), except for the 10-Hz threshold with the 1-mm contactor, which was the same as the difference found for 25 Hz with a 12.9-mm diameter contactor.

There were no significant correlations between the absolute thresholds at the thenar eminence, indicating that even if the same channel was responsible for mediating thresholds, other factors (contactor size and surround distance) had greater influences on the relative sensitivity of subjects. Significant correlations between absolute thresholds with the two contactors on the volar forearm with 125-Hz vibration suggest the same channel mediated perception at this location and frequency. The 10-Hz thresholds with both sizes of contactor on the volar forearm were also correlated with thresholds obtained with the 10-Hz thresholds obtained with the 1-mm contactor on the thenar eminence. Since 10-Hz thresholds with a 1-mm contactor on the thenar eminence were mediated by the NPI channel, it may be inferred that thresholds with both contactors on the volar forearm at 10 Hz were also mediated by the NPI channel. However, correlations between 10-Hz absolute thresholds of the two contactors at the volar forearm were not statistically significant, possibly due to the influence of factors other than the channel mediating perception.

8.4.2. Difference thresholds

Relative difference thresholds measured in this study were generally greater than those found in other studies. Craig (1972), Morioka (1998), and Forta *et al*. (2007, also see Chapter 5) reported relative difference thresholds between 0.15 and 0.20, whereas the lowest median difference threshold in this study was 0.20 and the highest was 0.58. One difference between the current study and both Morioka (1998) and Forta *et al*. (2007) is the contact conditions. Excitation of the whole hand results in more cues for subjects to detect differences than when only a small area of skin is excited, as in the current study. Craig (1972) employed a 6 mm diameter contactor with 2 mm gap between the contactor and the surround, and vibration was input to the fingertip. He tested two trained female subjects, compared to the 12 untrained males in the current study.

Gescheider *et al*. (1990, 1994a, 1996a, 1997a) used similar contact conditions to the current experiment and reported relative difference thresholds of about 0.24 with a 2.9-cm^2 contactor (19.2-mm diameter) and 250-Hz vibration, similar to the current experiment with the 10-mm diameter contactor and 125-Hz vibration at 15 dB SL (i.e., 0.24), but much lower than at 10 dB SL (i.e. 0.36). Gescheider *et al*. (1990) also found relative difference thresholds of about 0.24 using a 2.9 cm^2 contactor with 25-Hz vibration at 10 dB SL, lower than the 0.40 found in the current study with the 10-mm contactor at 10 Hz. At 20 dB SL, the difference between the studies is even greater.

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

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

The relative difference thresholds depended on frequency only when the 1-mm contactor was used, with the 125 Hz relative difference thresholds generally lower than the 10-Hz relative difference thresholds. This may be due to the involvement of the P channel in some cases or, alternatively, the NPII channel response may be involved in the perception of 125 Hz vibration. Gescheider *et al*. (1997) suggest the NPII channel might have lower relative difference thresholds than the P channel. If this is the case, it may have lowered the 125-Hz relative difference thresholds obtained with the 1-mm contactor at the thenar eminence at 10 dB SL, as well as lowering the relative difference thresholds at higher sensation levels with both contactors. At the higher sensation levels, the relative difference thresholds were similar for the 1-mm and 10-mm contactors at the thenar eminence at 125 Hz. According to the four-channel model of Bolanowski *et al*. (1988), the distance between the absolute thresholds of the P and the NPII channels is about 25 dB SL at 125 Hz on the thenar eminence. The higher sensation level used in the current experiment was 30 dB SL with the 1-mm contactor, high enough to excite the NPII channel. However, with the 10-mm contactor the higher level (15 dB SL) may not have excited the NPII channel. The 2-mm gap to the surround with the 10-mm contactor was larger than used in other studies and with the 1-mm contactor in the present study, possibly increasing the NPII threshold since the NPII channel is sensitive to skin stretch. However, the contact area was smaller (0.8 cm^2) than used by Bolanowski *et al.* and Gescheider *et al*. (2.9 cm^2), so higher P-channel thresholds would be expected in the present study, reducing the gap between the absolute thresholds of the two channels. Whether a rise in NPII thresholds (due to the greater surround gap) or a rise in P thresholds (due to reduced contact area) reduced the separation between the thresholds of the two channels to less than the 25 dB reported by Bolanowski *et al*. (1988), is unclear. It is therefore not possible to say whether 15 dB SL was sufficient to excite the NPII channel at the thenar eminence when the 10 mm contactor was employed.

The reduction in relative difference threshold with increased contactor size at the thenar eminence with 10-Hz vibration at 10 dB SL is unlikely to have resulted from spatial summation, but might have been due to a greater area or volume of tissue being excited, giving additional cues to detection. However, this was not observed with 125-Hz vibration where the relative difference was less with the 1-mm contactor than with the 10-mm contactor. Less transmission of the 125-Hz vibration compared to the 10 Hz vibration may also have contributed to the difference between the frequencies.

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

8.5. CONCLUSION

Although relative difference thresholds obtained from the response of the P-channel were lower than relative difference thresholds obtained from the response of the NPI-channel, the difference was marginally non-significant. If differences in discriminative ability exist between these two channels, they may be too low to be observed because other factors also influence relative difference thresholds. This conclusion agrees with the findings from the earlier experiments of this thesis which were conducted with different hand postures or vibration at other input locations.

Activity of the NPII-channel may have reduced the relative difference thresholds for 125-Hz vibration when using a 1-mm contactor at 10 and 30 dB SL.

CHAPTER 9: GENERAL DISCUSSION

9.1. INTRODUCTION

The five experiments of this thesis investigated various aspects of intensity difference thresholds for vertical vibration using psychophysical methods.

Experiment I found that for vertical sinusoidal whole-body vibration of seated persons, median relative intensity difference thresholds in the frequency range 2.5 to 315 Hz varied between 0.09 and 0.20, similar to those reported previously by other researchers for a more restricted range of vibratory stimuli (Chapter 4).

Experiment II found that for 16-Hz vertical sinusoidal vibration the median relative intensity difference thresholds of the hand with a grasping posture were in the range 0.16 to 0.20. For 125-Hz vibration the relative difference thresholds were in the range 0.15 to 0.23 (Chapter 5).

Experiment III obtained the relative intensity difference thresholds for foot-transmitted sinusoidal vibration from a footpad. The median values were between 0.19 to 0.27 for 16-Hz vibration and between 0.17 and 0.34 for 125-Hz vibration (Chapter 6).

Experiment IV obtained the relative intensity difference threshold for vertical hand-transmitted 125-Hz sinusoidal vibration masked by narrow-band random vibration centred on 16 Hz, with a hand grasping posture. The median unmasked relative difference thresholds were about 0.3 (Chapter 7).

Experiment V obtained relative intensity difference thresholds using two different contact conditions at the thenar eminence of the hand and the volar forearm. The median values on the thenar eminence were in the range 0.20 to 0.58. On the volar forearm, they were between 0.36 and 0.55 (Chapter 8).

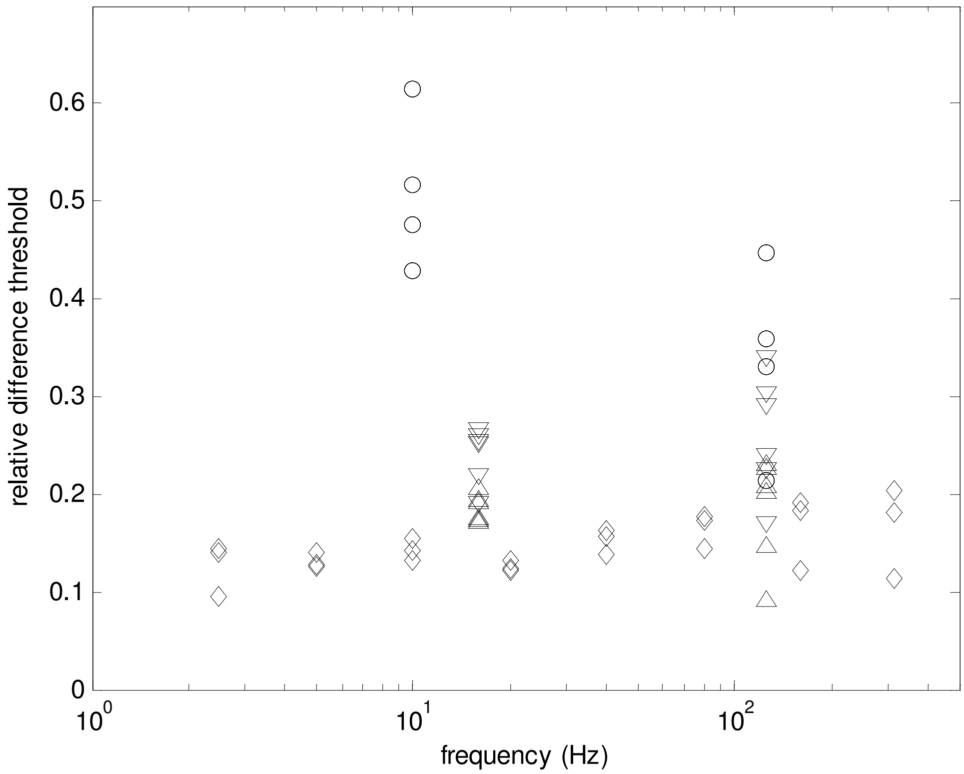


Figure 9.1. Relative difference thresholds by frequency. Relative difference thresholds from Experiments I, II, III and V are shown. Experiment I: diamonds, experiment II: upward-pointing triangles, experiment III: downward-pointing triangles, experiment V: circles.

Figure 9.1 shows the relative difference thresholds obtained from four of the experiments.

The aim of this thesis, is to investigate the effects of vibration frequency, magnitude, masking and somatosensory channel mediation on relative intensity difference thresholds of vertical sinusoidal vibration. This chapter aims to bring together the findings from the five experiments regarding these questions, and to look at the implications of these findings on other factors possibly affecting the relative difference thresholds, such as vibration input location, excitation area, perception by visual and auditory systems, and psychophysical the measurement method.

9.2. EFFECT OF VIBRATION FREQUENCY

Earlier studies have investigated the effect of frequency of vibration on intensity difference thresholds, but failed to find an effect for either hand-transmitted or whole-body vibration.

9.2.1. Whole body-vibration

The first experiment of the present thesis hypothesised that the relative difference thresholds for vertical seat-input whole-body vibration would depend on the vibration frequency. However, no significant dependency on frequency was found for any reference magnitude. Pielemeier *et al.* (1997) and Bellmann (2002) also failed to find a dependence of difference thresholds on vibration frequency. Morioka and Griffin (2000) reported relative difference thresholds slightly greater at 5 Hz compared to the relative difference thresholds at 20 Hz, but the difference was not significant. However, the study by Matsumoto *et al.* (2002) found a dependence on frequency: whole-body relative difference thresholds were smaller at 4 Hz compared to higher frequencies up to 63 Hz.

Even though differences in the difference thresholds between frequencies were not significant, a trend for greater relative difference thresholds at higher frequencies was observed for the low and middle magnitude conditions in the present study with whole-body vibration. There was a significant frequency effect for the high magnitude condition in this experiment, but this was likely to be due to the involvement of other sensory systems, as explained below in Section 9.5.

The trend for the relative difference thresholds to increase with increasing frequency may have resulted from the vibration being perceived in more locations at lower frequencies. The location of strongest sensation was determined in the experiment and revealed that, at higher frequencies, the vibration was perceived mostly in the areas of the body in contact with the seat (i.e. the input location).

Greater relative difference thresholds at higher frequencies may also suggest lower discriminative ability for the P channel, compared to the NP channels active at lower frequencies. Sensation levels for the vibration stimuli in the low magnitude condition in the experiment were between 5 and 10 dB, which means that the difference thresholds could have been mediated by single channels. At the sensation levels of the middle magnitude condition, between 15 and 25 dB SL, it was less likely that the difference thresholds were mediated by single channels, since, for example, 25 dB SL excitation above 80 Hz was likely to have excited one or more NP channel as well the P channel. This would have reduced difference thresholds at those frequencies if the NP channels have smaller difference thresholds than the P channel. However, the non-significant increasing trend was observed for both low and middle magnitude conditions, making it unlikely that differences in the discriminative abilities of the channels were responsible.

9.2.2. Hand-transmitted vibration

The second and fifth experiments of this thesis employed different frequencies to investigate difference thresholds for hand-transmitted vibration.

The relative difference thresholds obtained from vertical sinusoidal vibration with 16 Hz and 125 Hz were compared in the second experiment. At low magnitudes, the difference thresholds were expected to depend on frequency, as the thresholds were likely to be mediated by different somatosensory channels. However, while the 125-Hz relative difference thresholds were smaller than the 16-Hz relative difference thresholds at 12 dB SL, and greater at magnitudes above that level, the differences were not statistically significant. Morioka (2001) also found no differences between the relative difference thresholds at seven frequencies from 8 to 500 Hz for a handle grasping posture the same as used in the experiment.

The fifth experiment measured difference thresholds at the thenar eminence of the hand and at the volar forearm using 10 Hz and 125 Hz vibration. When the 1-mm diameter contactor with 1-mm surround gap was used, the 125-Hz relative difference thresholds were found to be smaller than the 10-Hz relative difference thresholds, for both contact locations. This difference may have arisen from the involvement of the NPII channel, which is sensitive to skin stretch, and therefore would not be as active when the 10 mm contactor with 2-mm gap was used.

9.2.3. Foot-transmitted vibration

Relative intensity difference thresholds were measured for footpad vibration in Experiment III. The stimuli were vertical sinusoidal vibration at 16 and 125 Hz, similar to those used in Experiment II. The relative difference thresholds were smaller for 125-Hz vibration at sensation levels below 12 dB, but above 12 dB SL, they were larger. However, as in the first two experiments, most differences were not statistically significant, except with 24 and 30 dB SL reference magnitudes.

It was concluded that significant differences may be due to a combination of the effect of the loss of discriminative ability within the P channel and the sensation being mediated by different channels with increasing magnitude. Overall, the frequency-dependence of relative difference thresholds in Experiment III was similar to the pattern found for the hand-transmitted relative difference thresholds in Experiment II. There are no known previous studies of difference thresholds for foot-transmitted vibration.

9.2.4. General effect

There seems to be no clear and systematic effect of vibration frequency on difference thresholds over all the conditions investigated. No significant frequency effects were observed for whole-body vibration or hand-input vibration when a large area of the body and the hand were excited. The frequency dependence seen for foot-transmitted vibration at high magnitudes may have been caused by differences in the pattern of vibration sensation observed at 16 and 125 Hz. The differences observed for hand-input vibration when using a small contactor might be due to the NPII channel having greater discriminative ability than the P channel.

9.3. EFFECT OF VIBRATION MAGNITUDE

Weber's Law predicts that the relative difference threshold is a constant (i.e. it does not change with a change in the stimulus reference magnitude). This general law of psychophysics was proposed for all sensory systems, and not specifically for vibration (Gescheider, 1985) For lifting weights, auditory noise and luminance, the relative difference thresholds decrease with increasing stimulus reference intensity starting from the absolute threshold level, and become near constant after a certain sensation level is reached. Similar trends for vibration have been observed by researchers for hand-input vibration (Craig, 1972).

9.3.1. Whole body-vibration

Experiment I of the current thesis investigated the effect of magnitude on whole-body vibration relative intensity difference thresholds, by employing three reference magnitudes at each of the eight test frequencies. An effect of magnitude was missing for frequencies from 5 to 160 Hz, but the relative difference thresholds for the high magnitude condition were found to be lower at 2.5 Hz and 315 Hz frequencies. This magnitude-dependence at the extremes of the investigated range was probably caused by additional cues from vision (at 2.5 Hz) and hearing (at 315 Hz). However, it is also possible that differences between the discriminative abilities of the somatosensory channels may have contributed to the magnitude-dependence, especially at 315 Hz.

The spreading of vibration was unlikely to have caused the observed pattern of responses during whole-body vibration. The distributions of the locations where the subjects perceived the vibration strongest were similar for the middle and high magnitude conditions, whereas the low magnitude condition often resulted in the vibration being felt strongest in a different location. The relative difference thresholds were only lower for the high magnitude condition. Had the spreading of the vibration been the main cause of the differences, they would have been expected between the low and middle magnitudes, at least at some frequencies.

The identity and characteristics of the somatosensory channels mediating whole-body vibration are not known. Nevertheless, differences in channel characteristics in regard to relative difference thresholds seem unlikely to be the primary cause of the observed patterns.

At 2.5 Hz, the middle magnitude corresponded to about 25 dB SL, while the high magnitude had a sensation level of about 35 dB SL. The difference of 10 dB SL between the two may have been sufficient for the high magnitude condition to excite another channel with a smaller relative difference threshold than the channels mediating the relative difference thresholds in the low and middle magnitude conditions. The four-channel model of the glabrous skin indicates that the NPIII channel (associated with Merkel disk endings) is the most likely candidate for involvement at lower frequencies. However, the absolute thresholds of the NPIII and NPI channels are close to each other for the glabrous skin, at frequencies up to about 10 Hz (Bolanowski *et al.*, 1988). For the hairy skin and the whole-body, it is not clear which channels are involved, but it is unlikely that an extra somatosensory channel was activated at between about 25 and 35 dB SL for 2.5-Hz vibration, but was absent at 5 Hz and 10 Hz. It is therefore unlikely that involvement of a new somatosensory channel with a lower relative difference threshold was responsible for the significantly lower relative difference thresholds at the high magnitude of 2.5-Hz vibration.

The vibration displacement at 2.5 Hz was clearly visible to the subjects, and it was likely to have supplied the subjects with cues to differences in vibration magnitude, allowing them to use the superior discriminative ability of the visual system to detect the differences.

At the other end of the frequency range (i.e. at 315 Hz), the middle and low magnitudes had sensation levels below about 15 dB SL, which may have been insufficient to excite multiple somatosensory channels, while the high magnitude condition was about 25 dB SL. The difference of 10 dB SL may be sufficient to excite an extra channel. The observed pattern may have resulted if the P channel determined the thresholds at high frequencies, but its absolute threshold had increased with increasing frequency. Speculating further, if the 25 dB SL excitation activated the NPII channel, and if the NPII channel has a smaller relative difference threshold than the P channel, the relative difference thresholds would have been expected to have reduced, as observed. A 1997 study by Gescheider *et al.*, suggests that the NPII channel may have smaller relative difference thresholds than the P channel. According to the four channel model of the glabrous skin (Bolanowski *et al.*, 1988), smaller relative difference thresholds were more likely to be observed at frequencies lower than 315 Hz, especially at 80 and 160 Hz, where both the P and NPII channels would be active. The relative difference thresholds obtained from the high magnitude condition at 80 and 160 Hz were indeed lower than the relative difference thresholds from the low and middle magnitudes, but the differences were not statistically significant. On the other hand, the absence of a surround and of significant skin stretch in the posture reduces the chances of NPII involvement in this experiment. It is therefore likely that there were other factors contributing to the significantly lower relative difference thresholds of the high magnitude condition at 315 Hz.

With the high magnitude at 315 Hz, the vibrator produced audible noise, which was used to determine the relative difference thresholds in a separate part of the experiment, where the subjects judged the stimuli solely by hearing, without contact with the seat. This experiment resulted in relative difference thresholds lower than the relative difference thresholds from the low and middle magnitude conditions, but higher than those from the high magnitude condition. The difference between the thresholds from hearing and high magnitude vibration, however, was not statistically significant. It is therefore likely that the subjects were able to get additional cues from the auditory system with the high magnitude vibration.

Other researchers who investigated magnitude effects of whole-body vibration (Morioka and Griffin, 2000; Mansfield and Griffin, 2000) failed to find statistically significant differences and concluded that Weber‘s Law applied.

9.3.2. Hand-transmitted vibration

The effect of magnitude on relative difference thresholds for vertical hand-transmitted vibration was investigated in Experiments II, IV and V of this thesis.

Experiment II employed a handle-grasping posture. For 16-Hz stimuli, the relative difference thresholds did not vary with varying magnitude. However, an effect of magnitude was observed for the 125-Hz stimuli, as the relative difference thresholds for reference magnitudes above 18 dB SL were significantly greater than the relative difference thresholds at 12 dB SL. This finding suggests that the discriminative ability of the P channel could have declined with increased excitation. The cause for this decline might be speculated as involving the saturation of the P channel with increasing vibration magnitude.

Experiment IV of the current thesis used the same posture as Experiment II, but there were differences in the psychophysical method, the stimuli, the number of subjects, and the number of sessions between the two experiments. Relative difference thresholds for 125-

Hz vibration were found to be similar at 9 dB SL and at 21 dB SL magnitudes, unlike the results of the second experiment. Differences in the test method may have resulted in the higher relative difference thresholds obtained in the fourth experiment as explained below (in Section 9.8). The shorter stimulus duration used in the fourth experiment may have raised the saturation magnitude of the P channel compared to the saturation magnitude in Experiment II. This may, in turn, have allowed the P channel to mediate the difference threshold at both 9 and 21 dB SL magnitudes. Also, while Experiment IV employed four subjects and 12 sessions per subject, Experiment II employed 12 subjects and two sessions per subject. This resulted in subjects having different experience in the difference threshold measurement procedure. In Experiment IV, two of the subjects had greater relative difference thresholds at 9 dB SL (as observed in Experiment II), while the other two had greater relative difference thresholds at 21 dB SL. Morioka (2001) tested the relative difference thresholds using a similar method and a similar posture to the ones used in this study. She did not find any significant magnitude effects.

Experiment V employed localised excitation on the thenar eminence of the hand and on the volar forearm, rather than the grasping posture used in Experiments II and IV. An effect of vibration magnitude on relative difference thresholds was observed only for the 125-Hz vibration applied to the thenar eminence using a 10-mm diameter contactor. When the vibration sensation level increased from 10 dB to 15 dB, the relative difference thresholds were reduced by about 0.1. The relative difference threshold at 15 dB SL was similar to the relative difference threshold obtained using the 1-mm diameter contactor at 30 dB SL, which may suggest that the NP II channel was involved in the mediation of the threshold in both conditions. However, the reduction in the relative difference threshold due to the increase in magnitude was only marginally significant (Wilcoxon, $p = 0.0425$) for the 10-mm diameter contactor.

Using 19-mm diameter contactors, studies by Gescheider and colleagues (1990, 1996a, 1997a) also reported reductions in relative difference thresholds with increasing vibration magnitude (from about 0.26 at 4 dB SL to 0.12 at 40 dB SL). These experiments used similar contact conditions to those in Experiment V, but tested different frequencies (25 and 250 Hz). The rate of the reduction observed by Gescheider and colleagues was only about 0.015 dB per dB increase in sensation level, which is much less than observed in Experiment V (about 0.55 dB per dB increase in sensation level). While both Experiment V and the Gescheider *et al*. (1997a) study suggest that the reduction may be due to the involvement of the NPII channel, given the differences between the rates of reduction, the subject populations, the stimuli and the test methods of the two studies, it is not possible to confirm that the NPII channel involvement is the cause of the observed magnitude effects at the thenar eminence of the hand.

9.3.3. Foot-transmitted vibration

Experiment III of the current thesis investigated the relative difference thresholds for foot-transmitted vibration with 16 Hz and 215 Hz vibration. It was found that, for 16 Hz vibration, the relative difference thresholds were consistent with Weber's Law (i.e. they did not depend on vibration magnitude). The relative difference thresholds at 30 dB SL were lower than the relative difference thresholds at other sensation levels, but this reduction was not statistically significant. Another cause of this reduction could be the spreading of the vibration at this magnitude, as discussed in Section 9.6.

The 125-Hz relative difference thresholds increased with increasing vibration magnitude. The curves showing how the relative difference thresholds depended on vibration magnitude were similar to those obtained for hand-transmitted vibration in Experiment II. In both cases the 125-Hz relative difference thresholds were smaller than the 16-Hz relative difference thresholds at the lowest reference magnitudes, but they increased with increasing magnitude, until they were greater.

There are no known studies on the effect of vibration magnitude on intensity difference thresholds at the foot, so no direct comparisons to studies from other researchers are possible.

9.3.4. General effect

There seems to be no effect of vibration magnitude on relative difference thresholds that is consistent for all contact conditions and all input locations. Effects of vibration magnitude were only observed for the frequencies greater than 40 Hz, other than for low frequencies of whole-body vibration where the motion was visible and high frequencies of whole-body vibration where the motion was audible. The magnitude-dependence observed for the P-channel range frequencies may be resulting from a loss of discriminative ability in the P channel. For the majority of the conditions investigated in the present thesis, the relative difference thresholds were independent of magnitude, as predicted by Weber's Law.

9.4. EFFECT OF MASKING

The effect of masking on difference thresholds was previously studied only for hand-transmitted vibration. Studies by Craig (1972) and Gescheider *et al*. (1992, 1994a) found that the relative difference threshold measured at a particular stimulus magnitude was increased by the addition of a masking stimulus. Both researchers employed vertical vibration (at 160 and 215 Hz) input to the hand through small contactors.

Experiment IV investigated the effect of masking on relative difference thresholds with stimuli applied to the whole hand at 125 Hz, at two magnitudes of 9 and 21 dB SL. The test and reference stimuli were presented within a 16-Hz continuous masker.

At the 9 dB SL reference magnitude, it was found that the 16-Hz centred third-octave noise masker did not have an effect on the relative difference thresholds of 125-Hz vibration when the masker magnitude was in the range 0 to 12 dB SL. At masker magnitudes of 18 and 24 dB SL, however, the relative difference thresholds were greater. The masked relative difference thresholds of all four subjects increased significantly with increasing masker magnitude. The curves suggest that the masker and the reference stimuli were initially detected by different somatosensory channels (likely to be NPI and P), so that increases in masker magnitude did not affect the relative difference thresholds until the masker (initially only detected by the NPI channel) reached a sufficiently high magnitude (about 12 dB SL in this experiment) to be detected by the channel mediating the relative difference threshold. In accord with the masking theory, when the masker and test stimuli were exciting different channels, masking did not occur (Gescheider *et al.*, 1982, 1985).

The results are consistent with separate information processing channels in the tactile system being responsible for the mediation of the relative difference thresholds at different magnitudes. In Experiment IV, the activation threshold of the P channel that mediated the threshold at 125 Hz, was likely to be about 12 dB above the threshold of the NP I channel that mediated the threshold of the 16-Hz masker frequency.

When the magnitude of the 125-Hz reference stimulus was raised to 21 dB SL, the trends were less clear. According to the findings from earlier experiments reported in this thesis, 21 dB SL may have been high enough to saturate the P channel, which would result in one or more other channels mediating the difference threshold. Had the P channel lost its ability to mediate the difference threshold and the NPI channel was responsible for the observed relative difference thresholds at that reference magnitude, the 16-Hz centred masker that primarily excited the NP I channel would be expected to affect the relative difference thresholds of the 125 Hz stimuli, even at masker magnitudes of 12 dB SL.

Increases in the relative difference thresholds for 125-Hz reference magnitude vibration were marginally significant for two of the four subjects. For one subject, the relative difference thresholds showed a trend to increase with increasing masker magnitude greater than 6 dB SL, suggesting that the NP I channel was involved in determining the difference thresholds at 125 Hz, as predicted. For the other three subjects, however, the relative difference thresholds remained mostly unaffected by the increase in the masker magnitude, except when the masker was at 24 dB SL, where they tended to be greater. Possibly, for these subjects, the P channel was still mediating the relative difference threshold, and even though the 16-Hz masker was high enough in magnitude to affect perception via the P channel, the amount of sensory input from the 16-Hz masker was small compared to the 21 dB SL excitation from the 125-Hz test stimuli. With 24 dB SL masker magnitude, the input from the masker to the P channel may have been high enough compared to the stimuli at 125 Hz, to cause the slightly higher relative difference thresholds at that masker magnitude.

The method of quantifying the reference excitation and the relative difference thresholds used the magnitude of the 125-Hz stimuli only, and did not take into account the masker magnitude. Even though the curves indicate an increase in the difference thresholds, the subjects may have produced only a constant relative difference threshold depending on the effect of the masker vibration. If the masker effect was added to the perception of the reference magnitude in a way that the relative difference threshold remained the same as the relative difference threshold without the masker effect (i.e. $\Delta I / I = \Delta I_m / I_m$), the masked relative difference thresholds would have differed from the relative difference thresholds measured with the method used in this experiment (i.e. $\Delta I_m / I$).

If it were possible to measure the P-channel excitation directly, including the effect of the masker, and the channel behaved in a perfectly Weberian way, the 'true' relative difference thresholds (Weber fractions) would have remained the same.

9.5. EFFECT OF INPUT FROM OTHER SENSORY SYSTEMS

Significant effects of vibration magnitude were observed at the extreme ends of the frequency range tested with whole-body vibration in Experiment I: at 2.5 Hz and 315 Hz.

During testing, it was apparent that vibration at 2.5 Hz was visible to the subjects. The subjects were vertically displaced by about 9.2 mm at the reference magnitude. The difference threshold corresponded to a vertical displacement of about 0.9 mm. Given the sensitivity of the visual system for discerning distances (0.001 according to Blake and Sekuler, 2006) and in visual acuity (0.017^{o} according to Wolfe *et al.*, 2006), this change in displacement was likely to have been seen by the subjects.

At the other end of the tested frequency range, the large vibrator produced an audible tone. It was not possible to completely mask the 315-Hz noise using white noise. The difference thresholds were measured with the subjects not in contact with the vibrator, but where they were able to hear the sound, and it was found that they produced relative difference thresholds similar to those obtained when they were in contact. It is therefore reasonable to conclude that the measured relative difference thresholds were smaller due to additional cues from the auditory system.

The findings from Experiment I seem to suggest that visual and auditory system involvement tends to reduce vibration intensity difference thresholds. Given the higher differential sensitivity of the auditory and the visual sensory systems, it is likely that these systems determine or influence the relative difference thresholds for vibration when the vibration exceeds their respective absolute thresholds.

Effects of other sensory systems were not observed in the other experiments, because the frequencies used in Experiments II, III IV and V were too low to hear and the frequencies were too high for the movement to be seen.

9.6. EFFECT OF EXCITATION AREA

The P channel possesses an ‘area summation’ capability: the absolute threshold of the channel is reduced with increasing excitation area. This effect is thought to be created by a combination of two mechanisms: ‘neural integration’, which means that the signals from individual Pacinian nerve endings are integrated by other structures of the nervous system to produce lower absolute thresholds, and ‘probability summation’, which means that the wider excitation area is more likely to excite individual Pacinian nerve endings that have lower thresholds than other Pacinian nerve endings (Gescheider *et al.*, 2009). Other identified somatosensory channels have not been proven to display spatial summation capability.

There are no known previous studies of difference thresholds that investigated the effect of excitation area. It is not inconceivable that the spreading of vibration would create a summation effect for the difference thresholds. For instance, when a stronger test vibration is compared to a reference vibration to determine the difference threshold, the sensation is likely to be different if the stronger vibration is spread to a larger area. The subjects could then be able to detect the difference not only by the amplitude difference (i.e. displacement on the skin) between the two vibrations, but also by the difference in the area excited by the stronger vibration.

Alternatively, a probability summation mechanism could exist for relative difference thresholds. If some areas of the skin or other tissues of the body had higher discriminative capability, experiencing the vibration in a wider area could result in the mediating of the difference threshold by more sensitive areas. This would result not in a true spatial summation effect observed for absolute thresholds of the P channel, but rather in a location summation effect.

Experiments I and III of this thesis investigated the locations of the excitation experienced by the subjects. Also, four different input locations that varied in excitation area, were used in the five experiments. Comparing the results of the four input conditions may produce clues to the effect of excitation area on the vibration difference thresholds.

Experiment I excited the largest area. Most of the excited skin was hairy, unlike the glabrous skin primarily excited in the other four experiments (except for the volar forearm in part of Experiment V). The relative difference thresholds measured in Experiment I tended to be lower than the relative difference thresholds measured in other experiments. The relative difference thresholds measured in Experiment I tended also to be lower at lower frequencies. The differences due to frequency were not statistically significant, but the trend seemed consistent. This trend could be partially caused by the spreading of the vibration. The lower frequencies excited more locations of the body, whereas the higher frequencies were confined to the seat-contact area. The difference perception may have benefited from the larger excitation area and deeper penetration of the lower frequency vibrations in this experiment.

In Experiment II, 16-Hz relative difference thresholds for hand-transmitted vibration with a grasping posture were smaller than the relative difference thresholds for 125 Hz vibration, from 18 to 36 dB SL reference magnitudes. With increasing vibration magnitude, the 16-Hz thresholds showed a non-significant trend to reduce from 6 dB SL to 36 dB SL (except for 30 dB SL). For 125Hz vibration, there was also a non-significant decrease in relative difference thresholds at 36 dB SL. Increased spreading of the vibration at 16 Hz compared to 125 Hz with increasing magnitude within each frequency, may have influenced the results. The effect would not be as pronounced for 125-Hz vibration, as this frequency mostly excited tissues near the contact surface.

Experiment III found that 16-Hz relative difference thresholds for foot-transmitted vibration were smaller than the relative difference thresholds for 125 Hz vibration with 12 to 30 dB SL reference magnitudes. The 16-Hz thresholds showed a non-significant decrease from 9 to 12 dB SL, and also from 24 to 30 dB SL with increasing magnitude. The locations of sensation were also recorded in this experiment. The results show that 16-Hz vibration was experienced at more locations as the magnitude of the vibration increased, which was not the case for the 125-Hz vibration, which was localised near to the surface of contact, regardless of the vibration magnitude. Also, at all vibration magnitudes 16-Hz vibration was experienced strongly in more than one location, whereas the 125-Hz vibration was always localised at the sole of the foot. These findings suggest that spreading of the vibration at 16 Hz could have contributed to smaller relative difference thresholds observed at that frequency at higher magnitudes.

The relative difference thresholds measured in Experiment IV were for 125-Hz vibration of the hand with a grasping posture. For two of the tested subjects, the 21 dB SL unmasked relative difference thresholds were lower at 9 dB SL, and for the other two subjects they were lower at 21 dB SL. The results indicate no systematic effect of vibration spreading in this experiment.

In Experiment V, spreading of the vibration on the skin surface was limited by the use of a surround. This experiment had the smallest excitation area used in the experiments, and produced the highest median relative difference thresholds. The size of the excitation area affected difference thresholds in two of the six test conditions. Both were on the glabrous skin of the thenar eminence, at 10 dB SL, one with 10 Hz vibration, and the other with 125 Hz. The lower thresholds coincided with the larger excitation area for 10-Hz vibration, but at 125 Hz the smaller excitation area produced the lower relative difference thresholds. Overall, no systematic effect of excitation area was seen in the results of Experiment V.

Comparison of the results from all experiments suggest that spreading of the vibration to wider areas and to a larger number of locations may reduce the relative difference thresholds, especially at low frequencies.

9.7. EFFECT OF INPUT LOCATION

Vibration was input to different parts of the body in the experiments of this thesis. All experiments used different conditions and methods, so a direct comparison of the effect of input location on relative difference thresholds is not possible. However, an indirect comparison may be useful, since there are no known studies dedicated to the effect of input location on relative difference thresholds.

In Experiment I, whole-body vibration was input through a rigid seat; in Experiments II and IV, vibration was input to the hand through a rigid handle; in Experiment III vibration was input to the foot via a foot-pad surface; and in Experiment V, vibration was input to the thenar eminence of the hand and to the volar forearm via 1-mm and 10-mm diameter contactors. Of these experiments, the fifth produced the largest relative median difference thresholds (approximately from 0.20 to 0.58), and the first produced the lowest (approximately from 0.10 to 0.20). Experiment II produced lower relative difference thresholds (approximately from 0.15 to 0.23) than Experiment III (approximately from 0.17 to 0.34) and Experiment IV (approximately 0.30).

The psychophysical method used in Experiments I and II was the same, and these two experiments produced the lowest relative difference thresholds. The relative difference thresholds tended to be lower in Experiment I, which may suggest that whole-body vibration produces lower relative difference thresholds than hand-transmitted vibration. On the other hand, the area of excitation was greater in Experiment I compared to Experiment II, which may have resulted in the tendency to produce lower relative difference thresholds for that input location.

Experiments II and IV used the same posture, but different methods, which is likely to have caused the higher thresholds measured in Experiment IV. Experiments III and V used the same psychophysical method, and Experiment III produced the lower relative difference thresholds. This does not necessarily mean that foot-input vibration produces lower difference thresholds, given the fact that the contact conditions varied greatly between these two experiments. The differences may also be due to the difference in contact conditions (i.e. effect of excitation area and surround) rather than the input location itself. Experiment V found that the relative difference thresholds at the thenar eminence of the hand tended to be lower than the relative difference thresholds on the volar forearm, but not significantly so.

Generally, there seems to be no obvious effect of input location on relative difference thresholds of vertical vibration. Where differences in relative difference thresholds were observed between the locations, they were more likely to be due to the differences in test methods and contact conditions rather than the effect of input location.

9.8. EFFECT OF TEST METHOD

As explained in Section 2.4.2, the effect of test method on vibration difference thresholds was investigated for hand-transmitted and whole-body vibration by other researchers. Using two-alternative forced- choice methods, one study found that the continuous-pedestal method produced lower difference thresholds compared to the gated-pedestal method for hand-input vibration. For whole-body vibration, Matsumoto *et al*. (2002) found that the vibration in the second interval was more likely to be judged relatively greater than the magnitude of the first vibration. Also, the researchers commonly attributed the differences between the difference threshold values they obtained on the differences in their methods, particularly in respect to the points on the psychometric function where they obtained the difference thresholds. Typically, difference thresholds obtained at lower correct response rates were lesser than difference thresholds obtained at higher correct response rates.

Relative difference thresholds from the last three experiments are not directly comparable to the relative difference thresholds from the first two experiments due to changes in vibration input location and signal duration. Nevertheless, comparison of similar conditions reveals higher relative difference thresholds for the later experiments.

Although the UDTR method (with gated pedestal) explained in Section 3 was used in all experiments, details of the measurement method varied between individual experiments. In the first two experiments, difference threshold tests started at a level near the difference threshold estimated from preliminary experiments. This meant that some of the subjects were unable to detect the difference between the test and the reference stimuli in the initial trial, due to inter- and intra- individual threshold differences. The three-down-one-up procedure used in the experiments allows the occurrence of three consecutive correct responses by chance even when the subject is not able to detect the magnitude difference between the test and reference stimuli. Such false reduction in level is statistically likely to happen once out of eight tests, when the tests start at a level the subject is not able to detect the differences between the two stimuli. False reductions are unlikely to affect the obtained thresholds unless when combined with other factors (e.g. subjects being tired) because the test procedure removes the first two reversals before calculating the threshold.

The difference in the magnitude of the stimuli started from levels greater than the difference threshold in the last three experiments of this thesis. Using this method, the subjects could relate to the task easily and the first reversals used in the calculation of the thresholds were always troughs.

Whether the minor differences in the psychophysical methods used in the different experiments of the current thesis affected the relative difference thresholds is not clear.

9.9. SOMATOSENSORY SYSTEM INVOLVEMENT

All experiments in this thesis were designed with the assumption that information processing channels exist in somatosensation. This assumption is well founded in the literature, having been developed since the 1960s by various researchers, as explained in Chapter 2. On the glabrous skin, for vibration frequencies from 2 Hz to 500 Hz and above, the absolute thresholds are mediated by two fast-adapting channels, or systems: the P and the NPI. Two more channels were identified for the glabrous skin, but their thresholds are higher than those of the fast-adapting systems under most conditions encountered in the environment.

While the characteristics of the channels are well known for mediation of absolute thresholds on the glabrous skin, their differential sensitivities are not similarly well known. Previous researchers, who discussed their findings of difference thresholds in terms of somatosensory channels, reported contradictory findings regarding whether differences in discriminative ability exist between the channels. For instance, Gescheider *et al.* (1990) found no difference between the relative difference thresholds of 25 Hz and 250 Hz vibration on the thenar eminence, but a later study, Gescheider *et al.* (1997a) suggested that the NPII channel may have had lower relative difference thresholds than the P channel. Shedding light on this subject is one of the aims of this thesis.

The first experiment in this thesis investigated a wide range of frequencies that may have excited channels on the glabrous skin but the vibration was input primarily to the hairy skin, and understanding of the channels in the hairy skin is limited. Nevertheless, frequencies above 40 Hz were expected to primarily excite the P channel, as is the case for hand-transmitted vibration. Had channels with differing relative difference thresholds existed in hairy skin, the differences would have been more likely to be observed as a dependency on vibration frequency for the lowest magnitude condition used in the experiment, because increasing vibration magnitude is likely to cause the excitation of multiple channels. The results from this experiment show that the relative difference thresholds tended to be higher at higher frequencies, but the differences were not significant. Even assuming that differences in discriminative ability between somatosensory channels existed, it is likely that factors other than differences between the channels, such as the effect of other sensory systems and contact conditions were more important in determining the relative difference thresholds in this experiment.

The second experiment tested two frequencies specifically chosen to excite primarily the NPI and P channels on the glabrous skin. At the lower magnitude (12 dB SL), the 16-Hz vibration was expected to excite the NPI channel, and the 125-Hz vibration was expected to excite the P channel. The relative difference thresholds for 125-Hz vibration were lower than the relative difference thresholds of the 16-Hz vibration, but the difference was not statistically significant. There were statistically significant differences between different magnitudes of 125 Hz vibration, but not between the relative difference thresholds of 125-Hz and 16-Hz vibration at any magnitude. At low magnitudes, the P channel may have lower relative difference thresholds than the NPI channel, but the results suggest that the difference is not large. As the discriminative ability of the P channel with 125 Hz vibration declined at higher magnitudes, an NP channel started to mediate the relative difference threshold (NPI or NPII). In any case, significant differences in relative difference thresholds were caused by changes within the P channel, rather than the differences between the P and NP channels. Results from Experiment IV, which used the same posture as Experiment II, indicate that 16-Hz vibration above 12 dB SL affects the relative difference threshold mediation at 125 Hz, which in turn suggests that for 16Hz vibration at magnitudes greater than 12 dB SL, the P channel could have been involved, but despite a reduction trend (which is in accord with the possibility of the P channel having slightly lower relative difference thresholds than the NPI channel), no significant differences were seen within the 16 Hz curve.

Experiment III used the same frequencies as Experiment II, to obtain the relative difference thresholds for foot-transmitted vibration. The results were similar to the results from Experiment II. At lower magnitudes of 6 and 9 dB SL, the relative difference thresholds for 125-Hz vibration were lower than the relative difference thresholds for 16-Hz vibration, but the differences were not significant. As the magnitude increased, the relative difference thresholds remained fairly flat for 16-Hz vibration, but they increased for 125-Hz vibration, as they did in Experiment II. This may be due to a decline in the discriminative ability of the P channel with increased excitation, possibly due to saturation.

The 16-Hz and 125-Hz relative difference thresholds were significantly different at 30 dB SL, with the 16-Hz relative difference thresholds being lower than 125-Hz relative difference thresholds, but analysis of the locations of sensation suggests this difference may be due to the spreading of the 16-Hz vibration at that magnitude, rather than a difference in the differential sensitivities between the channels. If a difference between the NPI and P channels exists, it would be more likely to be observed at lower magnitudes, where the thresholds were more likely to have been mediated by a single channel.

Experiment IV used narrow-band masker vibration centred at 16 Hz and reference vibration at 125 Hz. The masker was expected to excite the NPI channel and the 125-Hz vibration was expected to excite the P channel at 9 dB SL. It was found that the relative difference thresholds for 125-Hz vibration at 9 dB SL reference magnitude were masked by the 16-Hz narrow band noise, when the masker magnitude increased above 12 dB SL. This finding indicates that:

i. The relative difference threshold and the masker were mediated by separate channels.

ii. The distance in sensation level between the two channels was about 12 dB SL at 16 Hz.

The other reference condition in the experiment was 21 dB SL for 125-Hz vibration. At this reference magnitude the relative difference thresholds of two of the four subjects showed significant changes and the other two were relatively independent of masker magnitude. The relative difference thresholds of one of the subjects increased as soon as the masker magnitude was above the absolute threshold, which may indicate that for that subject 125-Hz vibration at 21 dB SL was sufficient to excite the NPI channel, which was affected by the masker immediately. For other subjects, it is likely that the relative difference thresholds were still mediated by the P channel at 21 dB SL, and did not increase as the masker magnitude increased until it was high enough to affect the P channel. While the masker sensation level required to mask the relative difference thresholds at 9 dB SL reference was above 12 dB, at 21 dB SL reference level it would be even higher, since the 21 dB SL is about four times greater in magnitude than 9 dB SL. Even when the gap between the absolute thresholds of two channels is the same, the same magnitude of masker input at both conditions would vary by a factor of four, in their proportion to the reference stimuli (i.e. the masking would start at a lower masker magnitude for a lower reference magnitude).

Experiment V employed vibration input to the glabrous skin on the thenar eminence of the hand and also to the hairy skin of the volar forearm to obtain the relative difference thresholds. The frequency, magnitude and contact conditions were chosen to isolate responses of the NPI and P channels. The results were similar to the findings in other experiments: the relative difference thresholds of the P channel were lower than the relative difference thresholds obtained from the NPI channel, but the difference was not statistically significant.

The dependence on contact area observed in Experiment V for 125-Hz vibration at 10 dB SL on the thenar eminence, suggests that the NPII channel, which is likely to have responded to the excitation by a small contactor and high skin stretch resulting from a narrow gap between the contactor and the surround when the 1-mm diameter contactor was used, had lower relative difference thresholds than other channels. Reduction in relative difference thresholds due to the involvement of NPII channel was not observed in Experiments II, III and IV of the thesis, despite the use of high magnitudes at 125 Hz, which may have activated the NPII channel according to Bolanowski *et al.* (1988). This was most probably due to the lack of a surround and very large contact areas used in Experiments II, III and IV. For 125-Hz vibration at 10 dB SL on the thenar eminence, higher sensation levels also produced similarly lower relative difference thresholds for both contactors, providing support to the suggestion that involvement of the NPII channel produced lower relative difference thresholds. Lower relative difference thresholds for the NP II channel were also suggested by Gescheider *et al.* (1997a), a study using similar contact conditions to Experiment V.

The nature of the somatosensory system in regard to channels is not well known for the hairy skin. Experiment V found that the relative difference thresholds at the thenar eminence of the hand tended to be lower than the relative difference thresholds on the volar forearm, but the differences were not significant, indicating that the relative difference thresholds might have been mediated by the same channels in both input locations.

General conclusions regarding the role of channels in mediating the relative difference thresholds are:

i. Results from Experiment IV indicate that the relative difference thresholds were mediated by individual channels, rather than derived at a higher point in the central nervous system from neural input from more than one channel.
ii. In four experiments, the P channel tended to have lower relative difference thresholds than the NPI channel at low sensation levels, but the difference between the two was not statistically significant.
iii. The discriminative ability of the P channel seemed to degrade at higher sensation levels (usually above 18 dB SL) for vibration input conditions with large contact areas, resulting in significantly increased relative difference thresholds at higher reference magnitudes, possibly due to the NPI channel having higher relative difference thresholds at those frequencies (possibly due to the sensation level in the NPI channel being near its absolute threshold).
iv. The findings in Experiment V suggest that the NPII channel may have produced lower relative difference thresholds than other channels.
v. The findings from the Experiment V suggest that the relative difference thresholds could have been mediated by similar systems in both the hairy skin and the glabrous skin for the conditions investigated.

9.10. SUMMARY

Experiments investigating the effects of some independent characteristics of vibration stimuli on relative difference thresholds found some effects, but the effects were not systematic in most cases and were attributed to factors other than the tested vibration characteristic. Such conclusions arise because independent variables such as vibration magnitude and frequency influence excitation area and tactile channel mediation, among other factors. For instance, when vibration frequency is increased, the excitation becomes less likely to be more transmitted to parts of the body other than the surface of the skin directly in contact with the vibration source, also, dependencies of the sensitivity of the somatosensory channels on frequency cause changes in perception. Similarly, when the vibration magnitude is increased, the transmission of the vibration to areas other than the immediate region of skin contact increases, and the number of channels responding to the vibration stimuli also tends to increase.

To summarise, the independent vibration characteristics of frequency, magnitude and duration do not directly affect the relative difference thresholds, but they affect a number of factors, including excitation area, which directly affect the relative difference thresholds.

Therefore, the independent vibration characteristics are designated ‘secondary factors’ and the direct factors are designated ‘primary factors’.

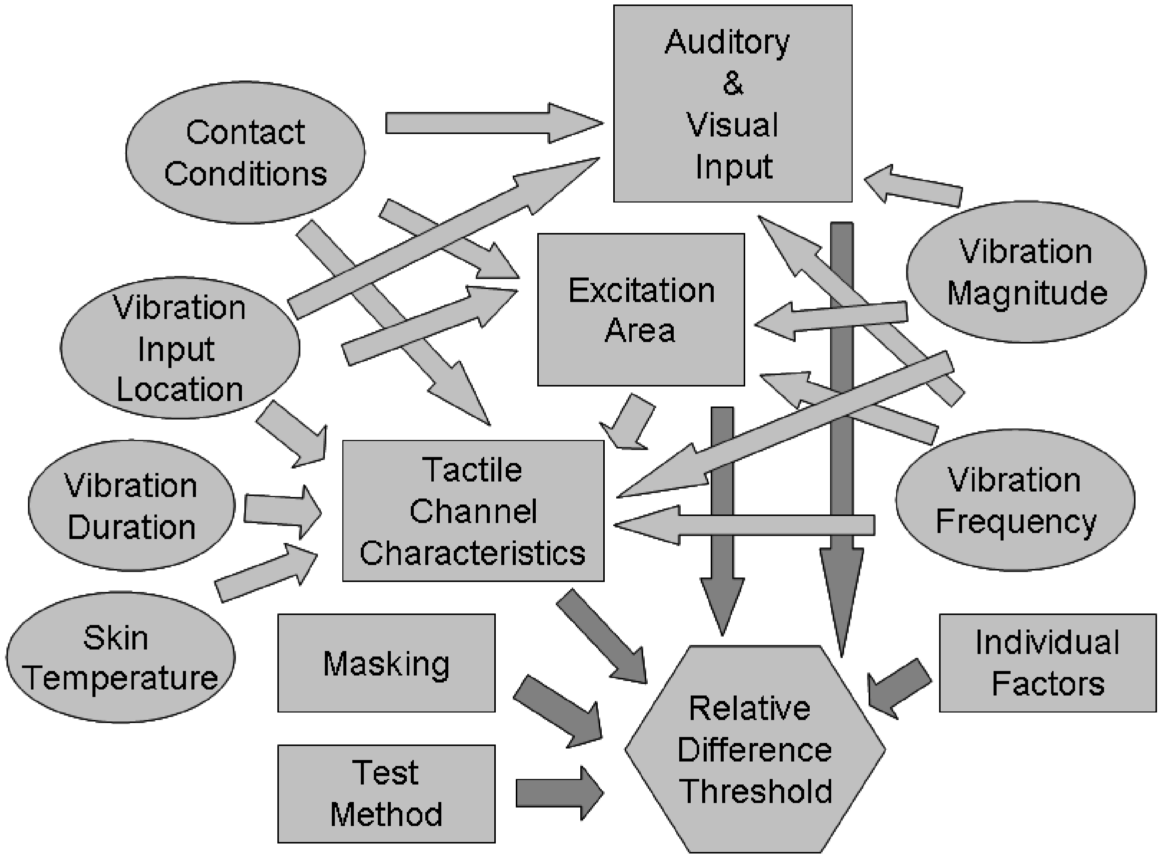


Figure 9.2. Factors affecting relative difference thresholds. Secondary factors are shown as oval shapes and the primary factors are shown as rectangular shapes.

A schematic model that details the relation of the secondary and primary factors with the relative difference thresholds is shown in Figure 9.2. Figure 9.2 is meant to be a map which shows how various factors relate to relative difference thresholds.

CHAPTER 10: CONCLUSIONS

10.1. GENERAL CONCLUSIONS

The goal of this thesis was to improve the understanding of the perception of vibration intensity difference thresholds. The review of the existing literature (Chapter 2) revealed that it is possible to advance knowledge in many aspects relating to difference thresholds and defined the focus of the current thesis as the effects of input location, excitation area, vibration frequency, vibration magnitude, and somatosensory channel mediation on difference thresholds.

Five experiments, each investigating one or more of the above aspects of difference threshold perception, were detailed in Chapters 4 to 8. The experimental chapters include the findings of individual experiments and the conclusions drawn from the findings and discussions of the individual experiments. Chapter 9 compared and contrasted the findings of the individual experiments and developed a conceptual model for the perception of differences in vibration intensity and arrived at conclusions beyond those reached within the context of individual experiments.

A summary of the general conclusions derived from the five experiments and the discussion are:

i. Relative difference thresholds can be mediated by changes in perception within individual channels – neural input from multiple channels is not required.
ii. Relative difference thresholds at the hairy skin were similar to those at the glabrous skin.
iii. A dependence of relative difference thresholds on vibration magnitude was only observed at frequencies greater than 40 Hz.
iv. The P channel tended to have lower relative difference thresholds than the NPI channel at sensation levels below 12 dB, but the difference between the two was not statistically significant.

v. The discriminative ability of the P channel seems to degrade at higher sensation levels (above about 18 dB SL) when large areas of the glabrous skin of the hand and the feet are excited.

vi. The NPII channel may have lower relative difference thresholds than the NPI and P channels in the glabrous skin.

vii. It is likely that when the visual and auditory systems are able to detect the vibration stimuli, the relative difference thresholds are lower than the relative difference thresholds mediated solely by the somatosensory system, due to better discriminative capabilities within the visual and auditory systems.

viii. Relative difference thresholds for vertical vibration tended to be smaller for input locations that excited greater areas of the body.

ix. When using the UDTR method, starting the difference threshold measurements close to the difference threshold of a subject tended to produce lower relative difference thresholds than starting the measurements at differences a subject can surely detect.

These conclusions help us to provide answers to some of the questions raised in Chapter 2, and mentioned above as the focus of the thesis.

For the majority of the conditions investigated in the thesis, the relative difference thresholds were independent of vibration magnitude, and therefore consistent with Weber's Law.

The relative difference thresholds obtained from the five experiments varied from about 0.1 to 0.6, depending on test conditions. There seems to be a trend for smaller relative difference thresholds with input locations that caused a large area of the body to vibrate (i.e. whole-body relative difference thresholds were the smallest while relative difference thresholds obtained with localised vibration at the hand and the forearm were the largest).

In three experiments that involved the glabrous skin, the P channel tended to have lower relative difference thresholds than the NPI channel below 12 dB sensation level, but the differences were not statistically significant. Where statistical differences between channels were observed, the reason tended to be a decline in the discriminative ability of the P channel above 18 dB SL or the involvement of the NPII channel, or a non-channel-related effect.

Inter-subject variance, the psychophysical test method used to measure the difference thresholds, and the input from senses other than touch are all primary factors directly affecting relative difference thresholds.

10.2. FUTURE WORK

While a considerable body of scientific knowledge exists on difference thresholds, all investigated factors can be revisited in new studies using neurological methods as well as psychophysical methods. Also, in addition to the already investigated factors, there remain dark areas that would benefit from dedicated studies.

i. Effect of the direction of vibration on difference thresholds

Unlike the absolute threshold studies, virtually all existing difference threshold studies employ vertical vibration (*z*-axis for the whole-body and *x*-axis for hand-transmitted vibration). Future research on vibration intensity difference thresholds for fore-and-aft and horizontal vibration would allow the comparison of the difference thresholds of the vibrations in different axes.

ii. Variability of difference thresholds and the effect of learning

Dedicated studies of intra- and inter-subject variability in difference thresholds would be useful, as the variability of the difference thresholds are not well known. Studies on intra-subject variability in difference thresholds can also be combined with studies of the effect of learning on difference thresholds.

iii. Comparison of the discriminative ability of the NPII and the P channels

Regarding the channel-dependence of relative difference thresholds, future studies focusing on mediation by the NPII channel may be helpful in shedding light on some of the observed dependencies of the difference thresholds on vibration frequency and magnitude.

iv. Investigation of the somatosensory perception at the hairy skin

Understanding of difference thresholds would benefit from investigation of somatosensory channel mediation in the hairy skin. Such studies will enable channel-based analysis of relative difference threshold data and more effective comparison of the data obtained from the hairy skin with the threshold data obtained from the glabrous skin.

v. Effect of psychological and cognitive factors on difference thresholds

Psychophysical methods employed in difference threshold measurements are usually more complex than those employed in absolute threshold measurements. This often results in increased demand on the physical and cognitive faculties of test subjects and may result in tiredness and loss of concentration, which may in turn have systematic effects on the perception of differences. A dedicated study of such factors will benefit understanding of vibration difference thresholds and inform the development of new test methods.

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APPENDIX A: INSTRUCTIONS

Written instructions given to the subjects in the five experiments are included in this appendix.

A.1. EXPERIMENT I

INSTRUCTIONS FOR THE DIFFERENCE THRESHOLD TEST

Thank you for taking part in this research project. This experiment aims to determine your difference thresholds for whole-body vibration at eight frequencies (2.5, 5, 10, 20, 40, 80, 160 and 315 Hz), and three magnitudes.

Before the experiment:

- Read the consent form and the health questionnaire carefully and fill them in.
- Mount the rig carefully.
- Put on the pair of headphones.
- Take the riding posture as instructed by the experimenter and maintain the same posture during the whole experiment.

During the experiment:

- You can stop the experiment at any time by informing the operator, or by pressing the stop button situated on the wall to your left.
- Keep your eyes on the red light. During testing, the light will go on for 2 seconds, will go off for 1 second and then go on again for another 2 seconds. In **both** of these 2-second periods, you will be presented with a motion.
- Concentrate on the motions and tell the operator in which period (i.e. 'first' or 'second') you felt, heard or saw **the stronger motion**.
- You may ask the operator for a repeat, if you wish to do so (e.g. in case of concentration loss).

After the experiment:

- Dismount the shaker carefully at the end of the experiment.

INSTRUCTIONS FOR THE LOCATION OF SENSATION TEST

Thank you for taking part in this research project. This experiment aims to determine at which parts of your body you feel the vibration at eight frequencies (2.5, 5, 10, 20, 40, 80, 160 and 315 Hz), and three magnitudes.

Before the experiment:

- Read the consent form and the health questionnaire carefully and fill them in.
- Mount the rig carefully, using the rigid step.
- Put on the pair of headphones.
- Take the riding posture as instructed by the experimenter and maintain the same posture during the whole experiment.

During the experiment:

- You can stop the experiment at any time by informing the operator, or by pressing the stop button situated on the wall to your left.
- Study the body map on the wall in front of you, where numbers are assigned to various parts of the body.
- During testing, you will be presented with a 2-second long motion.
- Concentrate on the motion and tell the operator the number (from the body map) corresponding to the body part where you felt the motion the strongest.
- You may ask the operator for a repeat, if you wish to do so (e.g. in case of concentration loss).

After the experiment:

- Dismount the shaker carefully at the end of the experiment.

A.2. EXPERIMENT II

INSTRUCTIONS FOR THE DIFFERENCE THRESHOLD TEST

Thank you for taking part in this research project. This experiment aims to determine your difference thresholds for hand vibration at six magnitude levels and two frequencies.

Before the experiment:

- Read the consent form and the health questionnaire carefully and fill them in.
- Mount the rig carefully.
- Put on the pair of headphones.
- Take the posture as instructed by the experimenter and maintain the same posture and grip on the handle during the experiment.

During the experiment:

- You can stop the experiment at any time by informing the operator.
- Keep your eyes on the red light. During testing, the light will go on for 2 seconds, will go off for 1 second and then go on again for another 2 seconds. In **both** of these 2-second periods, you will be presented with a motion.
- Concentrate on the motions and tell the operator in which period (i.e. 'first' or 'second') you experienced **the stronger motion**.
- You may ask the operator for a repeat, if you wish to do so (e.g. in case of concentration loss).

After the experiment:

- Dismount the rig carefully.

INSTRUCTIONS FOR THE PERCEPTION THRESHOLD TEST

Thank you for taking part in this research project. This experiment aims to determine your absolute perception thresholds for hand vibration at two frequencies.

Before the experiment:

- Read the consent form and the health questionnaire carefully and fill them in.
- Mount the rig carefully.
- Put on the pair of headphones.
- Take the posture as instructed by the experimenter and maintain the same posture and grip on the handle during the experiment.

During the experiment:

- You can stop the experiment at any time by informing the operator.
- Keep your eyes on the red light. During testing, the light will go on for 2 seconds, will go off for 1 second and then go on again for another 2 seconds. In **one** of these 2-second periods, you will be presented with a motion.
- Concentrate on the motions and tell the operator in which period (i.e. 'first' or 'second') you experienced **the motion**.
- You may ask the operator for a repeat, if you wish to do so (e.g. in case of concentration loss).

After the experiment:

- Dismount the rig carefully.

A.3. EXPERIMENT III

GENERAL INSTRUCTIONS FOR SUBJECTS

Thank you for taking part in this research project. In this experiment, you will be presented with a series of oscillatory motions (vibrations) at your right foot.

Three tests will be performed to determine:

- your ability to detect vibration stimuli (perception threshold test)
- the body location where you feel the vibration (location of sensation test)
- your ability to discriminate the intensity difference between two vibration stimuli (difference threshold test)

After the difference threshold tests, the perception threshold test will be repeated.

The Posture

Take your shoes off and keep your socks on. Fold your trousers so that your kneecaps are exposed. Make sure that the trouser folds will not move with the motion, and the socks do not have folds at the soles.

Mount and dismount the rig carefully.

During the experiment, sit comfortably on the saddle. Grasp both handles with a comfortable grip. Keep your feet flat on the wooden footrests at all times. Keep your eyes on the red light. Keep the same posture throughout the experiment. Refrain from moving, especially during measurement periods.

You can stop the experiment at any time by informing the experimenter.

INSTRUCTIONS PART 1.

PERCEPTION THRESHOLD TEST

Before the perception threshold determination:

- Put on the pair of headphones.

During the perception threshold determination:

- Keep your eyes on the red light. During testing, the light will go on for 2 seconds, will go off for 1 second and then go on again for another 2 seconds. In **one** of these 2-second periods, you will be presented with a motion.

- Your task is to judge in which period (i.e. ‘first’ or ‘second’) you experienced **the motion**.

- You may ask the operator for a repeat, if you wish to do so.

INSTRUCTIONS PART 2.

LOCATION OF SENSATION TEST

Before the location of sensation determination:

- Study the body map in front of you, where numbers are assigned to various parts of the leg.
- Put on the pair of headphones.

During the location of sensation determination:

- You will be presented with 2-second motions.
- After each motion, your task is to **tell the operator the numbers from the body map** corresponding to **all** the parts of the leg **where you felt the motion, starting with the location where you felt it the strongest.**
- You may ask the operator for a repeat, if you wish to do so.

INSTRUCTIONS PART 3.

DIFFERENCE THRESHOLD TEST

Before the experiment:

- Put on the pair of headphones.

During a difference threshold determination:

- Keep your eyes on the red light. During testing, the light will go on for 2 seconds, will go off for 1 second and then go on again for another 2 seconds. In **both** of these 2-second periods, you will be presented with a motion.

- Your task is to judge in which period (i.e. 'first' or 'second') you experienced **the stronger motion**.

- You may ask the operator for a repeat, if you wish to do so.

- Further pairs of motions will be presented for you to judge whether the first or second is stronger.

After a difference threshold determination:

- Study the body map in front of you, where numbers are assigned to various parts of the leg.

- You will be asked in which part of your leg you have experienced the difference between the two motions. Your task is to **tell the number from the body map** corresponding to the part of the leg **where you detected the difference between the two motions**.

- The testing will continue with the determination of the difference threshold at another intensity level. There are six levels in total.

A.4. EXPERIMENT IV

GENERAL INSTRUCTIONS FOR SUBJECTS

Thank you for taking part in this research project. In this experiment, you will be presented with a series of vibrations at your right hand.

Two types of tests will be performed to determine:

- your ability to detect vibration stimuli (perception threshold test)
- your ability to discriminate the intensity difference between two vibration stimuli (difference threshold test)

The number and order of tests will be as follows:

- One difference threshold test for training
- Two perception threshold tests (two frequencies)
- Six difference threshold tests (six masker levels)

Before the experiment;

- Complete the consent form and the health questionnaire
- Have your finger temperature measured

The Posture

Mount the rig carefully. During the experiment, sit comfortably on the saddle. Grasp both handles with a comfortable grip. Try to keep your grip on the right handle constant throughout the experiment.

Keep your feet flat on the wooden footrests at all times. Keep your eyes on the red light. Keep the same posture throughout the experiment. Refrain from moving.

You can ask for a break or stop the experiment at any time by informing the experimenter.

PERCEPTION THRESHOLD TEST INSTRUCTIONS

Before the perception threshold determination:

- Put on the pair of headphones.

During the perception threshold determination:

- During testing, you will be presented with a series of two periods. In **one** of these 1-second periods, you will be presented with a vibration (see the diagram in front of you).
- Your task is to judge in which period (i.e. ‘one’ or ‘two’) you experienced **the vibration**.
- You may ask the operator for a repeat, if you wish to do so.

- The testing will continue with the determination of the perception threshold with another vibration. There are two vibrations in total.

DIFFERENCE THRESHOLD TEST INSTRUCTIONS

Before the experiment:

- Put on the pair of headphones.

During a difference threshold determination:

- During testing, you will be presented with a series of three 1-second periods, the latter two of which may or may not be contained within a masker vibration (see the diagram in front of you). All three periods will contain high frequency ('buzz') vibrations. The first buzz is the initial period. The following two buzz periods are periods 'one' and 'two'.

- Concentrate on the buzz motions in the last two periods (periods 'one' and 'two'). Your task is to judge in which of these periods ('one' or 'two') you experienced **the stronger buzz**.

- You may ask the operator for a repeat, if you wish to do so.

- Further pairs of motions will be presented for you to judge whether the first or second is stronger.

- The testing will continue with the determination of the difference threshold at another intensity level. There are six levels in total.

A.5. EXPERIMENT V

INSTRUCTIONS FOR THE DIFFERENCE THRESHOLD TEST

Thank you for taking part in this research project. This experiment aims to determine your difference thresholds for vibration at two magnitudes, two frequencies and at two input locations.

Before the experiment:

- Read the consent form and the health questionnaire carefully and fill them in.
- Have your hand temperature taken.
- Put on the pair of headphones.
- Take the posture as instructed by the experimenter and maintain the same posture during the experiment. Keep the contact force at 100%.

During the experiment:

- You can stop the experiment any time by informing the operator.
- Keep your eyes on the red light. During testing, the light will go on for 1 second, will go off for 1 second and then go on again for another 1 second. In **both** of the 1-second periods when the light is on, you will be presented with a vibration.
- Concentrate on the vibrations and tell the operator in which period (i.e. 'first' or 'second') you experienced **the stronger vibration**.
- If you lose concentration, you may ask the operator for a repeat.

After the experiment:

- Remove the headphones.
- Have your hand temperature taken.

INSTRUCTIONS FOR THE ABSOLUTE THRESHOLD TEST

Thank you for taking part in this research project. This experiment aims to determine your absolute thresholds for vibration at two frequencies and two input locations.

Before the experiment:

- Read the consent form and the health questionnaire carefully and fill them in.
- Have your hand temperature taken.
- Put on the pair of headphones.
- Take the posture as instructed by the experimenter and maintain the same posture during the experiment. Keep the contact force at 100%.

During the experiment:

- You can stop the experiment any time by informing the operator.
- Keep your eyes on the red light. During testing, the light will go on for 1 second, will go off for 1 second and then go on again for another 1 second. In **one** of the 1-second periods when the light is on, you will be presented with a vibration.
- Concentrate on the vibration and tell the operator in which period (i.e. 'first' or 'second') you experienced **the vibration**.
- If you lose concentration, you may ask the operator for a repeat.

After the experiment:

- Remove the headphones.
- Have your hand temperature taken.

APPENDIX B: DIFFERENCE THRESHOLD DATA

Absolute and relative difference thresholds measured in the five experiments of the thesis are given in this appendix.

B.1.EXPERIMENT I

B.1.1. Absolute difference thresholds

Table B.1. Low magnitude condition. Rows: Subjects (1 to 12), columns: Frequencies (2.5, 5, 10, 20, 40, 80, 160, 315 Hz).

0.0052	0.0055	0.0047	0.0099	0.0043	0.0165	0.0264	0.1165
0.0049	0.0071	0.0036	0.0055	0.0067	0.0210	0.0434	0.0639
0.0089	0.0028	0.0056	0.0051	0.0061	0.0146	0.0281	0.0624
0.0072	0.0045	0.0138	0.0069	0.0072	0.0113	0.0187	0.0531
0.0110	0.0052	0.0155	0.0134	0.0104	0.0225	0.0506	0.0977
0.0140	0.0102	0.0098	0.0143	0.0074	0.0293	0.0329	0.1490
0.0114	0.0104	0.0066	0.0152	0.0079	0.0130	0.0616	0.0877
0.0067	0.0050	0.0051	0.0057	0.0063	0.0208	0.0329	0.1891
0.0094	0.0083	0.0049	0.0049	0.0046	0.0167	0.0265	0.0903
0.0050	0.0066	0.0066	0.0040	0.0019	0.0179	0.0400	0.0475
0.0058	0.0071	0.0067	0.0058	0.0077	0.0142	0.0530	0.0858
0.0047	0.0066	0.0083	0.0137	0.0085	0.0314	0.0545	0.0589

Table B.2. Middle magnitude condition. Rows: Subjects (1 to 12), columns: Frequencies (2.5, 5, 10, 20, 40, 80, 160, 315 Hz).

0.0214	0.0384	0.0290	0.0230	0.0327	0.1118	0.1765	0.3242
0.0354	0.0272	0.0382	0.0205	0.0290	0.0761	0.0603	0.2883
0.0279	0.0300	0.0507	0.0218	0.0275	0.0791	0.0848	0.2260
0.0105	0.0189	0.0217	0.0101	0.0185	0.0540	0.1603	0.2831
0.0465	0.0470	0.0299	0.0579	0.0527	0.0675	0.1321	0.2713
0.0482	0.0560	0.0540	0.0466	0.0402	0.0849	0.2744	0.3085
0.0411	0.0267	0.0329	0.0199	0.0330	0.0703	0.0985	0.2801
0.0284	0.0347	0.0719	0.0506	0.0352	0.1175	0.2277	0.5410
0.0188	0.0248	0.0219	0.0520	0.0129	0.0675	0.1842	0.2553
0.0232	0.0118	0.0088	0.0265	0.0153	0.0455	0.1446	0.2684
0.0297	0.0406	0.0346	0.0398	0.0335	0.0703	0.1724	0.1665
0.0309	0.0247	0.0117	0.0207	0.0134	0.0708	0.1049	0.2829

Table B.3. High magnitude condition. Rows: Subjects (1 to 12), columns: Frequencies (2.5, 5, 10, 20, 40, 80, 160, 315 Hz).

0.0664	0.1019	0.2089	0.1866	0.1564	0.2268	0.3756	0.6237
0.1246	0.1033	0.1132	0.0527	0.0716	0.2134	0.1230	0.7749
0.0964	0.0638	0.1685	0.1444	0.1509	0.2793	0.5610	0.4924
0.0710	0.0806	0.1397	0.0620	0.0987	0.2303	0.1429	0.4721

0.1102	0.0576	0.1163	0.1742	0.2458	0.1128	0.5590	1.0168
0.0538	0.1074	0.1254	0.1725	0.2349	0.2835	0.6631	1.0880
0.0735	0.1190	0.0805	0.1231	0.0418	0.0999	0.3945	0.6595
0.0834	0.1175	0.1850	0.1041	0.1339	0.4539	0.8102	0.8670
0.0524	0.1116	0.1068	0.0654	0.0805	0.3911	0.6370	0.2807
0.0739	0.0643	0.1116	0.1049	0.1177	0.2102	0.3792	0.9427
0.0993	0.1170	0.1009	0.0998	0.1277	0.1137	0.2762	0.9709
0.0772	0.0677	0.1076	0.0540	0.1360	0.2407	0.1946	0.6675

Table B.4. High magnitude condition. Rows: Subjects (1 to 12), column: 315 Hz Hearing only threshold.

0.7660
1.0696
1.0732
1.0950
0.7720
0.8766
0.9154
0.2773
0.8304
0.7166
0.4669
1.3903

B.1.2. Relative difference thresholds

Table B.5. Low magnitude condition. Rows: Subjects (1 to 12), columns: Frequencies (2.5, 5, 10, 20, 40, 80, 160, 315 Hz).

0.1031	0.1100	0.0944	0.2002	0.0856	0.1660	0.1346	0.2937
0.0976	0.1419	0.0708	0.1106	0.1352	0.2086	0.2165	0.1634
0.1767	0.0597	0.1126	0.1033	0.1227	0.1526	0.1438	0.1644
0.1461	0.0819	0.3122	0.1272	0.1416	0.1120	0.0946	0.1414
0.2194	0.1046	0.2943	0.2486	0.2009	0.2281	0.2535	0.2448
0.2879	0.1925	0.1890	0.2867	0.1475	0.3017	0.1647	0.3787
0.2275	0.2070	0.1308	0.2981	0.1587	0.1303	0.3141	0.2224
0.1340	0.0921	0.0981	0.1136	0.1277	0.2091	0.1660	0.4833
0.1892	0.1678	0.0961	0.0956	0.0910	0.1674	0.1324	0.1871
0.0983	0.1317	0.1346	0.0768	0.0370	0.1797	0.2020	0.1218
0.1157	0.1364	0.1329	0.1175	0.1554	0.1461	0.2669	0.2190
0.0931	0.1211	0.1624	0.2551	0.1628	0.2972	0.2645	0.1468

Table B.6. Middle magnitude condition. Rows: Subjects (1 to 12), columns: Frequencies (2.5, 5, 10, 20, 40, 80, 160, 315 Hz).

0.1074	0.1930	0.1444	0.1136	0.1673	0.2824	0.2178	0.2053
0.1756	0.1344	0.1938	0.1033	0.1482	0.1922	0.0764	0.1810
0.1407	0.1464	0.2520	0.1096	0.1412	0.2005	0.1063	0.1432
0.0528	0.0948	0.1112	0.0515	0.0905	0.1321	0.2001	0.1838
0.2295	0.2342	0.1471	0.2881	0.2676	0.1702	0.1652	0.1711
0.2343	0.2801	0.2687	0.2384	0.1940	0.2132	0.3471	0.1976
0.2034	0.1306	0.1618	0.1013	0.1674	0.1771	0.1228	0.1796
0.1421	0.1713	0.3593	0.2477	0.1709	0.2943	0.2878	0.3438
0.0906	0.1226	0.1079	0.2598	0.0621	0.1669	0.2307	0.1628
0.1166	0.0585	0.0441	0.1346	0.0772	0.1126	0.1807	0.1707
0.1452	0.1999	0.1756	0.2037	0.1665	0.1751	0.2160	0.1050
0.1552	0.1240	0.0597	0.1054	0.0672	0.1743	0.1315	0.1809

Table B.7. High magnitude condition. Rows: Subjects (1 to 12), columns: Frequencies (2.5, 5, 10, 20, 40, 80, 160, 315 Hz).

0.0825	0.1285	0.2613	0.2341	0.1953	0.1421	0.1173	0.0994
0.1569	0.1290	0.1419	0.0658	0.0901	0.1333	0.0383	0.1227
0.1208	0.0803	0.2080	0.1810	0.1898	0.1744	0.1737	0.0777
0.0877	0.1014	0.1733	0.0788	0.1239	0.1448	0.0449	0.0757
0.1400	0.0719	0.1440	0.2191	0.3072	0.0705	0.1749	0.1606
0.0668	0.1351	0.1577	0.2123	0.2900	0.1745	0.2076	0.1714
0.0919	0.1478	0.1000	0.1541	0.0515	0.0631	0.1235	0.1052
0.1040	0.1467	0.2315	0.1310	0.1690	0.2841	0.2520	0.1379
0.0658	0.1387	0.1347	0.0822	0.1013	0.2447	0.1986	0.0451
0.0929	0.0801	0.1398	0.1312	0.1468	0.1311	0.1186	0.1494
0.1231	0.1458	0.1252	0.1256	0.1585	0.0712	0.0858	0.1519
0.0967	0.0845	0.1354	0.0678	0.1716	0.1509	0.0606	0.1065

Table B.8. High magnitude condition. Rows: Subjects (1 to 12), column: 315 Hz Hearing only threshold.

0.1220
0.1703
0.1702
0.1465
0.1225
0.1456
0.1455

0.0439
0.1320
0.1135
0.0745
0.2210

B.2.EXPERIMENT II

B.2.1. Absolute difference thresholds

Table B.9. Vibration at 16 Hz. Rows: Subjects (1 to 12), columns: magnitudes (6, 12, 18, 24, 30, 36 dB SL).

0.0429	0.0385	0.0594	0.1653	0.5941	2.1046
0.0468	0.1349	0.2655	0.4252	0.7303	2.4625
0.0163	0.0417	0.1156	0.1989	0.4221	0.5350
0.0467	0.0989	0.2238	0.3771	0.4563	0.8478
0.0587	0.0626	0.1411	0.2492	0.5325	1.1066
0.0517	0.0914	0.2308	0.8387	1.0968	1.3635
0.0366	0.0969	0.1303	0.2274	0.5674	0.6370
0.0389	0.0417	0.1004	0.2649	0.4338	0.3919
0.0612	0.1104	0.3665	0.2534	0.5039	1.4506
0.0697	0.1459	0.1138	0.6452	1.2362	2.5800
0.0280	0.0485	0.0759	0.3178	0.3492	0.6485
0.0479	0.0827	0.1469	0.2990	0.3370	0.5831

Table B.10. Vibration at 125 Hz. Rows: Subjects (1 to 12), columns: magnitudes (6, 12, 18, 24, 30, 36 dB SL).

0.0023	0.0093	0.0256	0.0323	0.1209	0.1941
0.0033	0.0132	0.0270	0.0994	0.2294	0.1237
0.0015	0.0058	0.0187	0.0399	0.0723	0.1419
0.0118	0.0120	0.0282	0.0664	0.1903	0.5200
0.0029	0.0054	0.0101	0.0321	0.0458	0.1205
0.0031	0.0184	0.0239	0.0763	0.2254	0.3550
0.0034	0.0105	0.0390	0.0879	0.0960	0.1580
0.0018	0.0065	0.0192	0.0222	0.0711	0.1331
0.0024	0.0086	0.0279	0.0742	0.1490	0.4008
0.0042	0.0086	0.0105	0.0657	0.0914	0.2017
0.0045	0.0128	0.0273	0.0559	0.1360	0.3202
0.0021	0.0042	0.0223	0.0202	0.0303	0.1537

B.2.2. Relative difference thresholds

Table B.11. Vibration at 16 Hz. Rows: Subjects (1 to 12), columns: magnitudes (6, 12, 18, 24, 30, 36 dB SL).

0.2107	0.0978	0.0769	0.1083	0.1957	0.3323
0.2056	0.3043	0.2950	0.2417	0.2063	0.3489
0.0881	0.1170	0.1579	0.1393	0.1479	0.0925
0.1718	0.1803	0.2003	0.1719	0.1044	0.0972
0.3559	0.1959	0.2121	0.1895	0.2069	0.1916
0.2041	0.1781	0.2278	0.4082	0.2734	0.1694
0.1897	0.2516	0.1740	0.1476	0.1887	0.1060
0.1870	0.0993	0.1208	0.1612	0.1329	0.0612
0.2366	0.2215	0.3552	0.1235	0.1238	0.1781
0.2040	0.2118	0.0832	0.2397	0.2277	0.2602
0.2639	0.2229	0.1768	0.3714	0.2050	0.1909
0.2233	0.1914	0.1686	0.1714	0.0979	0.0836

Table B.12. Vibration at 16 Hz. Rows: Subjects (1 to 12), columns: magnitudes (6, 12, 18, 24, 30, 36 dB SL).

0.0744	0.1505	0.2108	0.1329	0.2510	0.2017
0.0839	0.1626	0.1806	0.3250	0.3843	0.1034
0.0675	0.1239	0.2102	0.2259	0.2015	0.2011
0.3204	0.1707	0.2074	0.2335	0.3321	0.4513
0.1122	0.1064	0.1006	0.1568	0.1102	0.1497
0.0918	0.2778	0.1850	0.3000	0.4352	0.3419
0.0795	0.1225	0.2359	0.2632	0.1442	0.1190
0.0768	0.1415	0.2076	0.1203	0.2004	0.1814
0.0920	0.1533	0.2657	0.3575	0.3612	0.4739
0.1241	0.1266	0.0754	0.2397	0.1650	0.1852
0.1305	0.1946	0.2033	0.2121	0.2492	0.2855
0.0947	0.0948	0.2475	0.1140	0.0855	0.2185

B.3.EXPERIMENT III

B.3.1. Absolute difference thresholds

Table B.13. Vibration at 16 Hz. Rows: Subjects (1 to 12), columns: magnitudes (6, 9, 12, 18, 24, 30 dB SL).

0.0115	0.0478	0.0467	0.0887	0.2064	0.2278
0.0346	0.0349	0.0400	0.0621	0.0976	0.2472

0.0144	0.0209	0.0229	0.0687	0.1180	0.2196
0.0140	0.0262	0.0444	0.0702	0.1198	0.1908
0.0184	0.0126	0.0186	0.0338	0.1508	0.1688
0.0138	0.0159	0.0134	0.0141	0.0533	0.1778
0.0262	0.0289	0.0362	0.1471	0.2478	0.5337
0.0294	0.0391	0.0362	0.1078	0.1460	0.1768
0.0115	0.0192	0.0316	0.0627	0.1077	0.1602
0.0218	0.0351	0.0328	0.0581	0.1301	2.5800
0.0121	0.0206	0.0399	0.0593	0.1288	0.2776
0.0186	0.0375	0.0433	0.0688	0.1873	0.1655

Table B.14. Vibration at 125 Hz. Rows: Subjects (1 to 12), columns: magnitudes (6, 9, 12, 18, 24, 30 dB SL).

0.0080	0.0096	0.0138	0.0525	0.0977	0.2847
0.0060	0.0031	0.0116	0.0337	0.0624	0.0937
0.0050	0.0067	0.0077	0.0233	0.0526	0.0988
0.0060	0.0049	0.0145	0.0215	0.0445	0.1355
0.0042	0.0145	0.0154	0.0342	0.0701	0.0642
0.0027	0.0033	0.0113	0.0146	0.0502	0.0994
0.0087	0.0119	0.0175	0.0479	0.0812	0.1777
0.0209	0.0191	0.0154	0.0625	0.1723	0.4995
0.0082	0.0066	0.0149	0.0378	0.0903	0.1652
0.0059	0.0070	0.0113	0.0194	0.0426	0.1128
0.0071	0.0186	0.0161	0.0480	0.1011	0.1856
0.0081	0.0061	0.0162	0.0403	0.0844	0.1933

B.3.2. Relative difference thresholds

Table B.15. Vibration at 16 Hz. Rows: Subjects (1 to 12), columns: magnitudes (6, 9, 12, 18, 24, 30 dB SL).

0.1255	0.3643	0.2502	0.2418	0.2805	0.1489
0.3785	0.2674	0.2234	0.1738	0.1399	0.1766
0.2669	0.2637	0.2151	0.3001	0.2805	0.2426
0.2082	0.2718	0.3202	0.2626	0.2135	0.1432
0.2992	0.1434	0.1473	0.1371	0.3092	0.1700
0.2864	0.2360	0.1438	0.0761	0.1407	0.2356
0.2280	0.1799	0.1714	0.3315	0.2941	0.3128
0.2913	0.2766	0.1882	0.2721	0.1852	0.1087
0.2559	0.2825	0.3143	0.3092	0.2763	0.2058
0.3336	0.3499	0.2299	0.2050	0.2316	0.2602

0.2484	0.2684	0.3733	0.3107	0.3307	0.3440
0.1698	0.2154	0.1925	0.1364	0.2085	0.0862

Table B.16. Vibration at 16 Hz. Rows: Subjects (1 to 12), columns: magnitudes (6, 9, 12, 18, 24, 30 dB SL).

0.1830	0.1574	0.1662	0.3152	0.3014	0.4051
0.2235	0.0787	0.2142	0.3226	0.2725	0.2187
0.2226	0.2268	0.1870	0.2822	0.3066	0.2969
0.2149	0.1228	0.2596	0.1905	0.1978	0.3210
0.1231	0.3166	0.2395	0.2584	0.2759	0.1271
0.0940	0.0851	0.1908	0.1332	0.2240	0.2319
0.3033	0.2929	0.3202	0.4468	0.3774	0.4280
0.2867	0.1827	0.1069	0.2113	0.3072	0.4363
0.2271	0.1509	0.2674	0.3022	0.3447	0.3321
0.2805	0.2326	0.2656	0.2316	0.2508	0.3511
0.2442	0.4409	0.2709	0.4249	0.4223	0.4290
0.2281	0.1197	0.2396	0.3049	0.3055	0.3517

B.4.EXPERIMENT IV

B.4.1. Absolute difference thresholds

Table B.17. Subject 1. 9 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.0788	0.0851	0.0880	0.0881	0.1058	0.1079
0.0673	0.0641	0.0659	0.0787	0.0979	0.0872
0.0960	0.0904	0.0931	0.1050	0.0880	0.1163
0.1030	0.1092	0.1277	0.1165	0.1376	0.1561
0.0679	0.0700	0.0830	0.0722	0.0781	0.0997
0.0658	0.0772	0.0717	0.0729	0.0692	0.0912

Table B.18. Subject 2. 9 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.0356	0.0384	0.0383	0.0454	0.0451	0.0471
0.0503	0.0544	0.0576	0.0556	0.0561	0.0716
0.0507	0.0507	0.0612	0.0469	0.0554	0.0561
0.0469	0.0486	0.0500	0.0576	0.0513	0.0619
0.0738	0.0741	0.0646	0.0657	0.0721	0.0829
0.1059	0.1059	0.1116	0.1060	0.1324	0.1353

Table B.19. Subject 3. 9 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.0628	0.0573	0.0687	0.0710	0.0654	0.0817
0.0653	0.0666	0.0656	0.0598	0.0647	0.0818
0.0617	0.0633	0.0663	0.0808	0.0689	0.0825
0.0816	0.0670	0.0706	0.0621	0.0694	0.0837
0.0567	0.0502	0.0469	0.0493	0.0594	0.0634
0.0532	0.0601	0.0574	0.0559	0.0594	0.0686

Table B.20. Subject 4. 9 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.0823	0.0870	0.0939	0.0890	0.0925	0.1165
0.0813	0.0869	0.0891	0.0913	0.1164	0.1306
0.0537	0.0557	0.0674	0.0590	0.0729	0.0835
0.0935	0.1016	0.0884	0.0906	0.1122	0.1275
0.0826	0.0986	0.1024	0.0910	0.1036	0.1258
0.0959	0.1041	0.1054	0.1049	0.1036	0.1146

Table B.21. Subject 1. 21 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.1712	0.1662	0.1968	0.1900	0.2042	0.2036
0.2133	0.2672	0.2370	0.2839	0.2973	0.2849
0.2369	0.2260	0.2290	0.2380	0.2365	0.2647
0.2335	0.2020	0.2261	0.2240	0.2144	0.2107
0.3360	0.3221	0.3631	0.3814	0.3826	0.3724
0.3026	0.2821	0.3370	0.2809	0.3002	0.3826

Table B.22. Subject 2. 21 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.1981	0.1909	0.1984	0.1980	0.2096	0.2096
0.2464	0.2142	0.2097	0.2247	0.2362	0.2350
0.2043	0.2155	0.1857	0.1889	0.1859	0.2084
0.2040	0.2191	0.2143	0.2168	0.2141	0.1930
0.1483	0.1713	0.1607	0.1686	0.1601	0.1697
0.2915	0.2982	0.2842	0.2717	0.2797	0.3443

Table B.23. Subject 3. 21 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.2453	0.2367	0.2579	0.2400	0.2363	0.2374
0.2053	0.2023	0.2132	0.2119	0.2100	0.2250

0.2816	0.2725	0.2831	0.2836	0.2676	0.3160
0.2412	0.2412	0.2141	0.2487	0.2185	0.2391
0.1916	0.1837	0.2139	0.1984	0.1817	0.2119
0.2330	0.2595	0.2473	0.2403	0.2374	0.2461

Table B.24. Subject 4. 21 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.3239	0.3162	0.3328	0.3352	0.3380	0.3171
0.2684	0.2553	0.2994	0.2864	0.2721	0.2968
0.4399	0.4718	0.4987	0.4760	0.5532	0.4688
0.5253	0.4751	0.4260	0.4867	0.4967	0.5091
0.2527	0.2369	0.2629	0.2285	0.2569	0.2937
0.4584	0.4006	0.3885	0.3909	0.3876	0.3938

B.4.2. Relative difference thresholds

Table B.25. Subject 1. 9 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.3531	0.4733	0.5202	0.5185	0.8256	0.8656
0.5779	0.4924	0.5391	0.8423	1.3276	1.0555
0.6518	0.5604	0.6113	0.8205	0.5239	0.9993
0.5467	0.6360	0.9104	0.7323	1.0461	1.3405
0.5534	0.6206	0.9159	0.6741	0.8104	1.3021
0.6541	1.0058	0.8412	0.8593	0.7585	1.3591

Table B.26. Subject 2. 9 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.1679	0.2560	0.2478	0.4900	0.4894	0.5841
0.1015	0.1893	0.2654	0.2142	0.2300	0.5717
0.1907	0.1933	0.4639	0.1011	0.2983	0.3136
0.1809	0.2175	0.2547	0.4323	0.2863	0.5659
0.2969	0.3014	0.1443	0.1658	0.2659	0.4737
0.1831	0.1815	0.2449	0.1838	0.4732	0.5137

Table B.27. Subject 3. 9 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.3058	0.1906	0.4348	0.4889	0.3671	0.7049
0.3370	0.3599	0.3446	0.2177	0.3259	0.6726
0.1568	0.1848	0.2454	0.5112	0.2969	0.5488
0.5663	0.2968	0.3574	0.1928	0.3467	0.6129

0.3709	0.2169	0.1380	0.1922	0.4317	0.5335
0.1050	0.2389	0.1884	0.1576	0.2254	0.4296

Table B.28. Subject 4. 9 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.2770	0.3525	0.4573	0.3816	0.4384	0.8125
0.2879	0.3852	0.4228	0.4562	0.8595	1.0761
0.4826	0.5270	0.8829	0.6152	1.0429	1.3135
0.4494	0.5735	0.3766	0.4072	0.7401	0.9934
0.2629	0.5072	0.5607	0.3883	0.5819	0.9271
0.3377	0.4513	0.4697	0.4622	0.4487	0.6058

Table B.29. Subject 1. 21 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.2811	0.2402	0.4692	0.4219	0.5301	0.5214
0.1983	0.5033	0.3308	0.5973	0.6869	0.6021
0.4563	0.3895	0.4039	0.4619	0.4505	0.6266
0.4373	0.2394	0.3907	0.3774	0.3172	0.2922
0.2980	0.2453	0.4066	0.4805	0.4814	0.4400
0.5454	0.4413	0.7216	0.4360	0.5443	0.9595

Table B.30. Subject 2. 21 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.2339	0.1881	0.2374	0.2370	0.3058	0.3055
0.3536	0.1766	0.1542	0.2326	0.2930	0.2930
0.2853	0.3608	0.1947	0.1913	0.1728	0.3113
0.1607	0.2482	0.2187	0.2341	0.2178	0.0993
0.0710	0.2372	0.1603	0.2162	0.1575	0.2251
0.2718	0.2969	0.2353	0.1843	0.2149	0.5023

Table B.31. Subject 3. 21 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.2086	0.1668	0.2715	0.1832	0.1656	0.1721
0.1697	0.1519	0.2153	0.2063	0.1958	0.2810
0.2308	0.1918	0.2372	0.2395	0.1704	0.3821
0.2922	0.2917	0.1473	0.3329	0.1717	0.2820
0.1743	0.1255	0.3093	0.2159	0.1133	0.2985
0.1498	0.2800	0.2207	0.1857	0.1716	0.2153

Table B.32. Subject 4. 21 dB SL reference. Rows: Days (1 to 6), columns: masker magnitudes (no masker, 6, 12, 18, 24, 30 dB SL).

0.4336	0.4016	0.4763	0.4842	0.4971	0.4053
0.3225	0.2623	0.4739	0.4126	0.3442	0.4649
0.3349	0.4367	0.5169	0.4502	0.6847	0.4245
0.5190	0.3748	0.2308	0.4121	0.4379	0.4741
0.4047	0.3169	0.4578	0.2655	0.4222	0.6263
0.8176	0.5870	0.5433	0.5512	0.5347	0.5576

B.5.EXPERIMENT V

B.5.1. Absolute difference thresholds

Table B.33. Contactor diameter 1 mm. Rows: Subjects (1 to 12), columns: test conditions (see Figure 8.4).

0.0942	1.9931	0.2409	2.7375	0.1909	1.3722
0.0718	1.2737	0.2147	2.0217	0.1490	11.7517
0.0427	0.9656	0.1658	1.3515	0.1246	2.9702
0.0645	0.5575	0.2188	1.4520	0.2400	4.1143
0.0736	1.6149	0.2777	3.5017	0.0918	0.8280
0.0784	2.5696	0.2300	8.5165	0.4254	4.8345
0.0654	0.3267	0.2303	2.6619	0.5017	2.0595
0.0548	0.8677	0.1457	1.0992	0.3298	2.4078
0.0402	0.7943	0.1382	2.6022	0.1670	3.6603
0.0437	0.7249	0.2115	0.4951	0.1682	1.0357
0.0830	0.8462	0.2692	0.6397	0.1976	3.8727
0.0562	0.7977	0.0584	1.0695	0.1778	1.3417

Table B.34. Contactor diameter 10 mm. Rows: Subjects (1 to 12), columns: test conditions (see Figure 8.4).

0.0451	0.2006	0.1871	2.3402	0.1032	0.8219
0.0305	0.2329	0.0939	1.9007	0.0915	1.7344
0.0335	0.2332	0.1386	1.9712	0.0471	0.8980
0.0470	0.0891	0.1052	0.9291	0.0717	1.3240
0.0248	0.3428	0.1174	1.6282	0.0565	1.9977
0.0275	1.1797	0.1110	3.3918	0.0813	1.1783
0.0122	0.2667	0.0711	1.9609	0.1959	1.3677
0.0364	0.2080	0.1478	2.2120	0.1076	2.0425
0.0344	0.5391	0.1162	1.3215	0.0769	1.8089
0.0511	0.5192	0.1102	4.0740	0.1023	1.3386

0.0551	0.2226	0.1379	1.5759	0.0692	1.1039
0.0251	0.3274	0.1456	3.4036	0.0528	0.5867

B.5.2. Relative difference thresholds

Table B.35. Contactor diameter 1 mm. Rows: Subjects (1 to 12), columns: test conditions (see Figure 8.4).

0.8251	0.3208	0.6223	0.2474	0.2667	0.2716
0.4943	0.2119	0.4206	0.1876	0.3532	1.0592
0.4846	0.1569	0.5651	0.1229	0.3057	0.4390
0.5256	0.1899	0.5856	0.2760	0.4778	0.3732
0.5605	0.2223	0.6022	0.2726	0.2150	0.0713
0.5150	0.3198	0.4824	0.5974	0.7544	0.2841
0.5597	0.0791	0.6326	0.3649	0.6800	0.4538
0.4011	0.3609	0.3400	0.2585	0.6147	0.3727
0.4352	0.1876	0.4684	0.3579	0.4563	0.3575
0.4776	0.5627	0.7118	0.2156	0.6497	0.2734
0.6217	0.1438	0.6085	0.0609	0.8197	0.3583
0.5176	0.1764	0.1654	0.1337	0.6135	0.3582

Table B.36. Contactor diameter 10 mm. Rows: Subjects (1 to 12), columns: test conditions (see Figure 8.4).

0.5000	0.3669	0.5984	0.4385	0.4409	0.3272
0.3276	0.3703	0.3577	0.3055	0.5462	0.5077
0.3935	0.2730	0.5640	0.2335	0.3170	0.3364
0.3992	0.1141	0.3144	0.1233	0.3738	0.5237
0.2779	0.3374	0.4200	0.1566	0.4973	0.6761
0.3363	0.7953	0.4366	0.2172	0.2840	0.2602
0.1458	0.3217	0.2735	0.2399	0.6872	0.7675
0.5010	0.3530	0.5494	0.3697	0.7230	0.3854
0.4728	0.5411	0.5104	0.1317	0.5932	0.6788
0.5856	0.6127	0.3829	0.4808	0.6947	0.5585
0.6129	0.2781	0.4978	0.2140	0.4535	0.1439
0.2800	0.3621	0.5085	0.3693	0.3642	0.2834

APPENDIX C: SAMPLE MATLAB SCRIPTS

Sample matlab scripts used to obtain the absolute and relative difference thresholds from the acceleration data are given in this appendix. Sample scripts included here are specific for the fifth experiment of this thesis. Absolute thresholds were also obtained by using similar scripts not included here.

C.1. SAMPLE SCRIPT TO CALCULATE DIFFERENCE THRESHOLDS

```
% this script:
%   - reads the acceleration data from the csv files of a subject
%   - finds the reversal points and calculates the absolute and relative
%   difference thresholds at the reversal points
%   - checks the number of reversal points and calculates the mean absolute
%    and mean relative difference thresholds depending on the number of
%    reversals
%   - writes the results to individual matrix (change for all subjects)
%   - copy for all conditions and subjects
% ngf 04.04.08

% read csvs one at a time
for z=1:7;
   if z==1;
      R = CSVREAD('2101.csv',1,0);
   elseif z==2;
      R = CSVREAD('2201.csv',1,0);
   elseif z==3;
      R = CSVREAD('3101.csv',1,0);
   elseif z==4;
      R = CSVREAD('3201.csv',1,0);
   elseif z==5;
      R = CSVREAD('4101.csv',1,0);
   elseif z==6;
      R = CSVREAD('4201.csv',1,0);
   else z==7;
      R = CSVREAD('2101T.csv',1,0);
end

% find reversal points and calculate thresholds at reversal points
A=[R(:,1) R(:,2) R(:,3)];
siz=size(A,1)-1;
fil=0;
tog=2;
j=0;
for i=1:siz;
   fil=A(i+1,1)-A(i,1);
      if fil==1 | fil==2;
```

```
        if tog==0;
            j=j+1;
            AT(j,1)=A(i,2)-A(i,3);
            RT(j,1)=AT(j,1)/A(i,3);
        else
        end
    tog=1;
    elseif fil==-1;
        if tog==1;
            j=j+1;
            AT(j,1)=A(i,2)-A(i,3);
            RT(j,1)=AT(j,1)/A(i,3);
        else
        end
    tog=0;
    else
    end
end

clear R
clear A

% calculate mean thresholds depending on the number of reversals
revnum = size(AT,1);
    % reversal check
    ATMOD=AT;
    atsiz=size(ATMOD,1);
    if atsiz==4;
        ATMOD(5:9,1)=0;
    elseif atsiz==5;
        ATMOD(6:9,1)=0;
    elseif atsiz==6;
        ATMOD(7:9,1)=0;
    elseif atsiz==7;
        ATMOD(8:9,1)=0;
    else atsiz==8;
        ATMOD(9,1)=0;
    end
    DT12C_1(z,1:9)=ATMOD';
    %calculate threshold
```

```
if revnum < 4;
   AA(1,z) = mean(AT,1);
   RA(1,z) = mean(RT,1);
elseif revnum==4 | revnum==5;
   AT=[AT(3,:); AT(4,:)];
   RT=[RT(3,:); RT(4,:)];
   AA(1,z) = mean(AT,1);
   RA(1,z) = mean(RT,1);
elseif revnum >= 6;
   AT=[AT(3,:); AT(4,:); AT(5,:); AT(6,:)];
   RT=[RT(3,:); RT(4,:); RT(5,:); RT(6,:)];
   AA(1,z) = mean(AT,1);
   RA(1,z) = mean(RT,1);
end
clear AT
clear RT
end
% write the results to individual matrix, to be changed manually for other subjects
AD12_1=AA(1:6)
RD12_1=RA(1:6)
TS12_1=[AA(7) RA(7)]
DT12C_1

clear AA
clear RA
return
```

C.2. SAMPLE SCRIPT FOR DATA ANALYSIS

```
% this script
%       - runs the individual scripts for all subjects and conditions and compiles the results
%       into absolute and difference threshold matrices
%       - calculates the medians and inter-quartile ranges for all results and plots them
%       - performs friedman and wilcoxon tests on the result matrices as appropriate
%       - repetitive parts are omitted
% ngf 09.04.2008

% obtain matrices: AT with 1mm
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S1\AT_1');
at1s1;
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S2\AT_1');
at1s2;
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S3\AT_1');
at1s3;
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S4\AT_1');
at1s4;
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S5\AT_1');
at1s5;
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S6\AT_1');
at1s6;
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S7\AT_1');
at1s7;
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S8\AT_1');
at1s8;
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S9\AT_1');
at1s9;
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S10\AT_1');
at1s10;
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S11\AT_1');
at1s11;
cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results\S12\AT_1');
at1s12;
% repetition for AT with 10 mm, DT with 1 mm and DT with 10 mm omitted

cd('C:\Documents and Settings\user\My Documents\gizem\experiment 5\results');
 AA_1 =[A1_1 A2_1 A3_1 A4_1 A5_1 A6_1 A7_1 A8_1 A9_1 A10_1 A11_1 A12_1]'
```

```
AA_10=[A1_10 A2_10 A3_10 A4_10 A5_10 A6_10 A7_10 A8_10 A9_10 A10_10 A11_10
A12_10]'
 MA_1  = median(AA_1)
MA_10 = median(AA_10)
 AD_1 =[AD1_1; AD2_1; AD3_1; AD4_1; AD5_1; AD6_1; AD7_1; AD8_1; AD9_1; AD10_1;
AD11_1; AD12_1]
AD_10=[AD1_10; AD2_10; AD3_10; AD4_10; AD5_10; AD6_10; AD7_10; AD8_10; AD9_10;
AD10_10; AD11_10; AD12_10]
 ARD_1 =[RD1_1; RD2_1; RD3_1; RD4_1; RD5_1; RD6_1; RD7_1; RD8_1; RD9_1; RD10_1;
RD11_1; RD12_1]
ARD_10=[RD1_10; RD2_10; RD3_10; RD4_10; RD5_10; RD6_10; RD7_10; RD8_10; RD9_10;
RD10_10; RD11_10; RD12_10]
 MRD_1  = median(ARD_1)
MRD_10 = median(ARD_10)
 PER=[75 25];
AA_1_IQR=prctile(AA_1,PER);
AA_10_IQR=prctile(AA_10,PER);
ARD_1_IQR=prctile(ARD_1,PER);
ARD_10_IQR=prctile(ARD_10,PER);

% plots
plotax1=[0.9 1.9 2.9 3.9];
plotax10=[1.1 2.1 3.1 4.1];
iqraa1x=[0.9 1.9 2.9 3.9; 0.9 1.9 2.9 3.9];
iqraa10x=[1.1 2.1 3.1 4.1; 1.1 2.1 3.1 4.1];
figure
semilogy(plotax1,MA_1,'k.')
hold on
semilogy(iqraa1x(:,1),AA_1_IQR(:,1),'b-');
hold on;
semilogy(iqraa1x(:,2),AA_1_IQR(:,2),'b-');
hold on;
semilogy(iqraa1x(:,3),AA_1_IQR(:,3),'b-');
hold on;
semilogy(iqraa1x(:,4),AA_1_IQR(:,4),'b-');
hold on;
semilogy(plotax10,MA_10,'ko')
hold on
semilogy(iqraa10x(:,1),AA_10_IQR(:,1),'b-');
hold on;
```

```
semilogy(iqraa10x(:,2),AA_10_IQR(:,2),'b-');
hold on;
semilogy(iqraa10x(:,3),AA_10_IQR(:,3),'b-');
hold on;
semilogy(iqraa10x(:,4),AA_10_IQR(:,4),'b-');
axis([0 5 0.01 10])
%legend('median 1 mm', 'median 10mm')
set(gca,'xtick',[1 2 3 4]);
%title('Absolute thresholds and interquartile ranges');
xlabel('absolute threshold test condition');
ylabel('acceleration (ms^{-2} r.m.s.)');
% plotting script repeated for relative difference threshold (omitted)

% Hypothesis testing: effect of condition
friedman_ARD_1 = friedman(ARD_1,1,'off')
friedman_ARD_10 = friedman(ARD_10,1,'off')
% Testing the inter-subject variability
friedman_ARD_1_isv = friedman(ARD_1',1,'off')
friedman_ARD_10_isv = friedman(ARD_10',1,'off')
% wilcoxon tests within 1mm relative difference threshold results
[o_1_o_2,QQ1]=SIGNRANK(ARD_1(:,1),ARD_1(:,2));
[o_1_o_3,QQ2]=SIGNRANK(ARD_1(:,1),ARD_1(:,3));
[o_1_o_4,QQ3]=SIGNRANK(ARD_1(:,1),ARD_1(:,4));
[o_1_o_5,QQ4]=SIGNRANK(ARD_1(:,1),ARD_1(:,5));
[o_1_o_6,QQ5]=SIGNRANK(ARD_1(:,1),ARD_1(:,6));
[o_1_t_1,QQ6]=SIGNRANK(ARD_1(:,1),ARD_10(:,1));
[o_1_t_2,QQ7]=SIGNRANK(ARD_1(:,1),ARD_10(:,2));
[o_1_t_3,QQ8]=SIGNRANK(ARD_1(:,1),ARD_10(:,3));
[o_1_t_4,QQ9]=SIGNRANK(ARD_1(:,1),ARD_10(:,4));
[o_1_t_5,QQ10]=SIGNRANK(ARD_1(:,1),ARD_10(:,5));
[o_1_t_6,QQ11]=SIGNRANK(ARD_1(:,1),ARD_10(:,6));
% Wilcoxon tests for other  comparisons are omitted

return
```

APPENDIX D: QUESTIONNAIRES

The health questionnaires used in the experiments to pre-screen subjects and to gather personal data are included in this appendix.

D.1. EXPERIMENT I

HEALTH QUESTIONNAIRE

REF. NO.____________

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

Section A: Personal information

Name: ____________________ Age: _________ Date of Birth: ___

Nationality: ____________________ Height: _________ cm Weight: ________ kg

Occupation: Student [ ] Staff [ ] Other [ ]

Section B: Health information

1. **Do you smoke?**

YES [ ] NO [ ] If yes, please specify the number: [______] of cigarettes a day

2. **How much alcohol do you consume weekly?**

Never [ ] 1-3 units* [ ] 4-6 units [ ] More than 6 units [ ] * 1 unit for a glass of wine, 2 units for a pint of beer

3. **Do you drive?**

YES [ ] NO [ ] If yes, please specify how frequent: [______] hours a week

4. **Do you ride a motorbike?**

YES [ ] NO [ ] If yes, please specify how frequent: [______] hours a week

5. **Do you exercise regularly?**

YES [ ] NO [ ] If yes, what sports do you participate in? ________________________]

6. **Do you take any drugs or medication?**

YES [ ] NO [ ] If yes, please specify _________________________________

7. **Have you had any back surgery?**

YES [ ] NO [ ] If yes, please specify _________________________________

9. **Have you had trouble (such as ache, pain, discomfort, numbness) in your body?**

YES [ ] NO [ ] If yes, please specify where in your body:

Elbows [ ] Wrists/hands [ ] Back [ ] Neck [ ] Shoulder [ ] Hips/thighs [ ] Knees [ ] Ankles/feet [ ]

10. **Do you suffer from the following disorders?**

Diabetes [ ] Digestive disorders [ ] Vascular problems [ ] Neuropathy problems [ ] Urinary disorders [ ] Vestibular disorders [ ] Others__________ None [ ]

11. **Have you been exposed to severe or long periods of vibration such as:**

Vibration tools [ ] Off-ad vehicles [ ] Trucks [ ] Motorbikes [ ] Others _____ Never [ ]

D.2. EXPERIMENT II

HEALTH QUESTIONNAIRE

REF. NO.____________

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

Section A: Personal information

Name: ___________________ Age: _________ Date of Birth: ______

Nationality: ___________________ Height: _________ cm Weight: __________ kg

Occupation: Student [ ] Staff [ ] Other [ ]

Section B: Health information

1. Do you smoke?

YES [ ] NO [ ] If yes, please specify the number: [______] of cigarettes a day

2. How much alcohol do you consume weekly?

None [ ] 7 units or less [ ] more than 7 units [ ] * 1 unit for a glass of wine, 2 units for a pint of beer

3. How much cafein do you consume per week?

None [ ] 14 units or less [ ] more than 14 units [ ] * 1 unit for a glass of tea or cola, 2 units for a cup of coffee

3. Do you ride a motorbike?

YES [ ] NO [ ] If yes, please specify how frequent: [______] hours a week

4. Do you exercise regularly?

YES [ ] NO [ ] If yes, what sports do you participate in? [____________________]

5. Do you take any drugs or medication?

YES [ ] NO [ ] If yes, please specify ________________________________

6. Have you had any hand-arm surgery?

YES [ ] NO [ ] If yes, please specify ________________________________

7. Have you had trouble (such as ache, pain, discomfort, numbness) in your body?

YES [ ] NO [ ] If yes, please specify where in your body:

Elbows [ ] Wrists/hands [ ] Back [ ] Neck [ ] Shoulder [ ] Hips/thighs [ ] Knees [ ] Ankles/feet [ ]

8. Do you suffer from the following disorders?

Diabetes [ ] Digestive disorders [ ] Vascular problems [ ] Neuropathy problems [ ] Urinary disorders [ ] Vestibular disorders [ ] Others ____________________

None [ ]

9. Have you been exposed to severe or long periods of vibration such as:

Vibration tools [ ] Off-ad vehicles [ ] Trucks [ ] Motorbikes [ ] Others _______________

Never [ ]

D.3. EXPERIMENT III

HEALTH QUESTIONNAIRE

REF. NO.____________

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

Section A: Personal information

Name: ____________________ Age: _________ Date of Birth: __________

Nationality: ____________________ Height: _________ cm Weight: __________ kg

Occupation: Student [ ] Staff [ ] Other [ ]

Section B: Health information

1. Do you smoke?

YES [ ] NO [ ] If yes, please specify the number: [______] of cigarettes a day

2. How much alcohol do you consume weekly?

Never [ ] 1-3 units* [ ] 4-6 units [ ] More than 6 units [ ] * 1 unit for a glass of wine, 2 units for a pint of beer

3. Do you drive?

YES [ ] NO [ ] If yes, please specify how frequent: [______] hours a week

4. Do you ride a motorbike?

YES [ ] NO [ ] If yes, please specify how frequent: [______] hours a week

5. Do you exercise regularly?

YES [ ] NO [ ] If yes, what sports do you participate in? [________________________________]

6. Do you take any drugs or medication?

YES [ ] NO [ ] If yes, please specify _________________________________

7. Have you had any surgery on your right leg or foot?

YES [ ] NO [ ] If yes, please specify _________________________________

9. Have you had trouble (such as ache, pain, discomfort, numbness) in your body?

YES [ ] NO [ ] If yes, please specify where in your body:

Elbows [ ] Wrists/hands [ ] Back [ ] Neck [ ] Shoulder [ ] Hips/thighs [ ] Knees [ ] Ankles/feet [ ]

10. Do you suffer from the following disorders?

Diabetes [ ] Digestive disorders [ ] Vascular problems [ ] Neuropathy problems [ ] Urinary disorders [ ] Vestibular disorders [ ] Others ____________________

None [ ]

11. Have you been exposed to severe or long periods of vibration such as:

Vibration tools [ ] Off-road vehicles [ ] Trucks [ ] Motorbikes [ ] Others ____________________

Never [ ]

D.4. EXPERIMENT IV

HEALTH QUESTIONNAIRE

REF. NO.____________

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

Section A: Personal information

Name: ___________________ Age: _________ Date of Birth: __________

Nationality: ___________________ Height: _________ cm Weight: __________ kg

Occupation: Student [ ] Staff [ ] Other [ ]

Section B: Health information

1. Do you smoke?

YES [ ] NO [ ] If yes, please specify the number: [______] of cigarettes a day

2. How much alcohol do you consume weekly?

Never [ ] 1-3 units* [ ] 4-6 units [ ] More than 6 units [ ] * 1 unit for a glass of wine, 2 units for a pint of beer

3. Do you drive?

YES [ ] NO [ ] If yes, please specify how frequent: [______] hours a week

4. Do you ride a motorbike?

YES [ ] NO [ ] If yes, please specify how frequent: [______] hours a week

5. Do you exercise regularly?

YES [ ] NO [ ] If yes, what sports do you participate in? [___________________]

6. Do you take any drugs or medication?

YES [ ] NO [ ] If yes, please specify ________________________________

7. Have you had any surgery on your right leg or foot?

YES [ ] NO [ ] If yes, please specify ________________________________

9. Have you had trouble (such as ache, pain, discomfort, numbness) in your body?

YES [ ] NO [ ] If yes, please specify where in your body:

Elbows [ ] Wrists/hands [ ] Back [ ] Neck [ ] Shoulder [ ] Hips/thighs [ ] Knees [ ] Ankles/feet [ ]

10. Do you suffer from the following disorders?

Diabetes [ ] Digestive disorders [ ] Vascular problems [ ] Neuropathy problems [ ] Urinary disorders [ ] Vestibular disorders [ ] Others ____________________

None [ ]

11. Have you been exposed to severe or long periods of vibration such as:

Vibration tools [ ] Off-road vehicles [ ] Trucks [ ] Motorbikes [ ] Others ____________________

Never [ ]

D.5. EXPERIMENT V

HEALTH QUESTIONNAIRE

REF. NO.____________

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

Section A: Personal information

Name: ___________________ Age: _________ Date of Birth: __________

Nationality: ___________________ Height: _________ cm Weight: __________ kg

Handedness: Right [ ] Left [ ]

Occupation: Student [ ] Staff [ ] Other [ ]

Section B: Health information

1. **Do you smoke?**

   YES [ ] NO [ ] If yes, please specify the number: [______] of cigarettes a day

2. **How much alcohol do you consume weekly?**

   Never [ ] 1-3 units* [ ] 4-6 units [ ] More than 6 units [ ] * 1 unit for a glass of wine, 2 units for a pint of beer

3. **Do you drive?**

   YES [ ] NO [ ] If yes, please specify how frequent: [______] hours a week

4. **Do you ride a motorbike?**

   YES [ ] NO [ ] If yes, please specify how frequent: [______] hours a week

5. **Do you exercise regularly?**

   YES [ ] NO [ ] If yes, what sports do you participate in? [______________________________]

6. **Do you take any drugs or medication?**

   YES [ ] NO [ ] If yes, please specify ________________________________

7. **Have you had any surgery on your right hand or arm?**

   YES [ ] NO [ ] If yes, please specify ________________________________

9. **Have you had trouble (such as ache, pain, discomfort, numbness) in your body?**

   YES [ ] NO [ ] If yes, please specify where in your body:

   Elbows [ ] Wrists [ ] Hands [ ] Back [ ] Neck [ ] Shoulder [ ] Hips/thighs [ ] Knees [ ] Ankles/feet [ ]

10. **Do you suffer from the following disorders?**

    Diabetes [ ] Digestive disorders [ ] Vascular problems [ ] Neuropathy problems [ ] Urinary disorders [ ] Vestibular disorders [ ] Others ______ None [ ]

11. **Have you been exposed to severe or long periods of vibration such as:**

    Vibration tools [ ] Off-road vehicles [ ] Trucks [ ] Motorbikes [ ] Others ___ Never [ ]