WAVE INTERACTION IN ROTARY VIBRO-TACTILE DISPLAYS FOR HUMAN COMMUNICATION

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ABSTRACT

This project began with the aim of developing an efficient vibrotactile communication device. A review of existing devices, mainly designed for speech communication, suggested that although adding an extra stimulator can improve the performance in some situations, it can degrade the performance in another situation. To explain these varied results, the properties of the human vibrotactile system involved in the perception of mechanical stimuli were studied. This study suggested that there is a great deal of interaction within the vibrotactile perceptual system, part of which is essential for a stimulus to be perceived. It also raised the question regarding the relative importance of the interaction which takes place prior to the tactile receptor as opposed to that occurring from the receptor onwards.

Methods to reduce this interaction were introduced and on this basis a novel rotary vibrator was developed. A psychophysical method specifically aimed at measuring the interaction at the level between the stimulation site and the tactile receptors was developed. This method is based on the detection of "beats" arising from stimulation of two vibrators at slightly different frequencies.

A system capable of driving a pair of similar vibrators at approximately 15dB SL over the frequency range of 25-500Hz was developed. The results of the psychophysical tests show that the introduced method of measuring interaction is indeed a practical method. In addition, the data from this study suggest that there is a difference between the perceived level of interaction from the two types of vibrators. The interaction is less in the case of the rotary vibrator compared to the conventional perpendicular vibrator at frequencies lower than about 50Hz. These findings offer a new way to look at the development of future vibrotactile devices.

IN THE LOVING MEMORY OF MY
LITTLE BROTHER…

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Those who have passed through the period of studying for a Ph.D. perhaps would agree that by no means it can be considered an easy period of one's life. Yet, it seems that the difficult periods remain in one's memory and as the time passes by, it becomes sweeter by recalling the picture of those whom this time was shared with. They are numerous faces that are going to stay in my mind.

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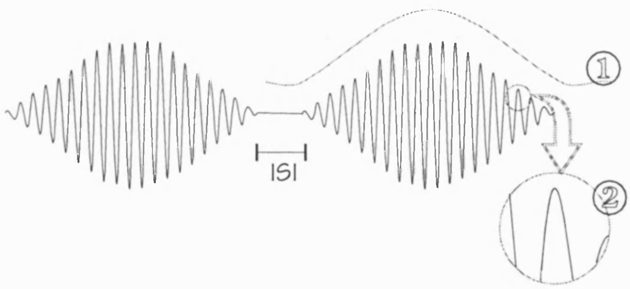
LIST OF TERMS AND ABBREVIATIONS

Burst-shape	See figure below (1)
CD	Contactor Diameter
CNS	Central nervous system
CST	Complete set of test
f	Frequency
ID	Indentation
ISI	Inter Stimulus Intervals
SD	Surround Diameter
SF	Static Force
Tadoma	A natural method of tactile communication
Threshold of sensitivity	Detection threshold
Waveform	See figure below (2)
σ	Standard deviation



CHAPTER 1

INTRODUCTION

1.1 Definition of tactile communication

Tactile communication refers to the use of touch as a means of information exchange. There are numerous methods of tactile communication, falling into two main categories, natural and artificial (Reed, 1995). The artificial methods (also referred to as "synthetic" - Watson *et al.*, 1991) are defined as those that require an electrical or mechanical transducer, whereas natural methods do not. Tactual speech reading (including Tadoma), finger-spelling, tactual reception of sign languages, manual alphabets and Morse code are examples of natural tactile methods - details of each can be found in Watson *et al.* (1991). Some of these natural methods *do* perform well. However, the major shortcoming of natural methods is their requirement for close contact between the sender and receiver (Reed *et al.,* 1982; Watson *et al.,* 1991; Weisenberger, 1992; Reed, 1995). In an important sense, the primary aim of artificial tactile devices is to enable reception of acoustic signals through touch without direct contact between the receiver and transmitter.

How do artificial devices eliminate the need for close contact between sender and receiver? In general, a tactile device uses the information within acoustic or non-acoustic signals to generate a pattern that is believed to be most suitable for perception by touch. The tactile patterns then stimulate the recipient's afferent nerves either by direct electrical (electrotactile) or indirect mechanical (vibrotactile) stimulation, causing sensations associated to the original stimuli. This project concentrates on the vibrotactile approach.

1.2 Who benefits from tactile devices?

Research and development in tactile communication would benefit the following areas:

The hearing impaired

Hearing (and in particular hearing-vision) impaired individuals are the very first group attracted toward the capabilities of the tactile sense. Vibrotactile aids for transfer of auditory information been proven useful in providing a general awareness of environmental sounds and as a supplementary tool for speech training of hearing impaired people (Watson *et al.*, 1991; Weisenberger, 1991 and references therein).

Position awareness

The tactile channel is an alternative modality that can be used when other sensory modalities are overloaded. Some investigators proposed the use of tactile information as a solution for the problem of lack of orientation experienced in combat aircraft and in marine and other situations in which information regarding orientation may be required (see Cholewiak R., 2000; Greene, 2001).

Tele-touch and virtual reality

This new range of applications for tactile communication has emerged mostly during the past few decades. These devices aim to simulate the sensation of touch either from artificially generated sources or by transmitting the sensations from real objects. Although the scope of this field is larger than solely vibrotactile devices, sensations related to vibration such as surface texture and smoothness are considered directly related to the sense of vibration. It is expected that such a device may open new horizons in education, medicine, robotics and the entertainment industry. Despite extensive investment and research on the development of such devices, their utility is still unproven. For examples see Niki and Shimojo (2000) and Asamura *et al.* (1998b).

1.3 Why do we expect more from tactile devices?

What are the reasons for the strong belief that despite decades of effort, these devices are not yet utilising the full capability of the sense of touch?

Firstly, evidence from subjects' performance with natural methods suggests that performance using the tactile sense can be developed to high level (Watson *et al.*, 1991; Cowan *et al.*, 1995). Research has shown that the tactile sense is capable of receiving continuous discourse at near normal communication rate (Reed, 1992) and is adequate for the task of speech communication (Reed *et al*, 1982). This level of performance appears, at least in the case of Tadoma, to be superior to any artificial tactile devices for encoding speech signals (Watson *et al.*, 1991; Reed *et al.,* 1982; Snyder *et al.*, 1982; see discussion in Snyder *et al.* for a list of related experiments).

Secondly, whether the superior performance of Tadoma is due to extensive training of the user or the fact that the tactile method is not only depending on the sense of vibration (Reed *et al.,* 1982), there is no evidence to believe that these successful methods are yet utilising the maximum capacity of the sense of touch. There is some evidence which supports the possibility of improvement in performance. Reed (1995) shows that "cued Tadoma"- a method using hand actions similar to visual cueing - can further improve the performance over that of natural Tadoma. Reed *et al.* (1982) also demonstrates superior performance from vibrotactile devices which have dynamic tactile patterns over those with static patterns.

The third piece of convincing evidence that development of tactile devices is far from mature is from attempts to simulate the sensation of touch. Despite some recent developments (see for example Asamura *et al.*, 1998a,b; Watanabe and Fukui, 1995) there appears to be no device which is capable of simulating the sensations elicited by the touch of different materials. For additional evidence on the inadequacies of existing devices to use the capability of this sense and thus the need for further research, see Section 2.2.

In summary, given that we might expect considerably more from tactile devices, it is reasonable to ask where the limitations of current devices lie.

1.4 Structure of the thesis

The structure of this thesis is organised into three main sections as follows:

Section 1: Study of the human sense of touch and vibrotactile devices

A vibrotactile device works in conjunction with the human sensory system. In order to achieve understanding of the human sense of touch and vibrotactile devices, there are two separate chapters reviewing the appropriate literature.

Chapter 2, analyses various vibrotactile devices in order to understand the approaches used in existing devices. An attempt has been made to classify vibrotactile devices in terms of their main functional components. The performance of single and multichannel devices are compared in order to predict the benefit which could be obtained by increasing the number of vibrators in vibrotactile prostheses.

Chapter 3 studies the human vibrotactile sensory system in order to understand its behaviour. There are two perspectives which can be employed to obtain this understanding, namely 'stimulus and response' and a 'purely physical view'. To achieve this the relevant psychophysical and physiological studies are reviewed. The information in this chapter, together with that in Chapter 2, provides an estimate of the extent to which the requirements of this sensory system have been taken into account during the design of these devices.

Section 2: The hypothesis

Evidence from the reviews presented in Chapter 2 suggests that in general the data transmission rate of a vibrotactile device does not increase proportionally with the number of vibrators employed. The reviews given in Chapter 3 also reveal some generally accepted explanations for this phenomenon.

Chapter 4 presents a hypothesis regarding the extent to which mechanical interaction between waves is important in the perception of tactile stimuli. The chapter also includes suggestions for assessing this interaction and presents a framework for the following experimental work.

Section 3: The experimental work

An experiment was set up to test the hypothesis stated in section 2. Since the experiment was a comparative study, great effort was made to control the variables which would affect the relative measurements. In this respect, emphasis was put on the calibration of the device and its driving system.

Chapter 5 explains the design of the vibrators and equipment and their preparation for the experimental work.

Chapter 6 presents the development of the psychophysical test used and the results of employing the test on subjects. This chapter also describes the software which controls the psychophysical procedure.

Chapter 7 brings together the conclusions from the present study and discusses related issues. The thesis ends with suggestions for further work.

CHAPTER 2

FROM SOUND TO VIBRATION

2.1 Introduction

This chapter reviews the designs of vibrotactile devices and presents a picture of their current status. The reasons for this review is to understand the potential advantage of a particular design and to realise those parameters that may have contributed to the limitations in their performance. These points are essential and similarly important for the design of any successive device.

2.2 Variation in design (functional classification)

Early vibrotactile designs investigated the possibility of tactile communication through simple approaches. In general, these devices vibrated the skin directly with speech vibrations.

Later, as knowledge regarding the tactile sense, mostly in respect to its frequency and intensity dynamic range was improved, a further step was taken to improve the performance of tactile devices. Versions of these latter designs developed around a common concept of spreading the speech information to a number of vibrators and hence improve the information transmission rate. Multi-channel devices are defined here and referred hereon as devices with more than one vibrator. Following are examples from different methods using multi-vibrators to convey speech information.

2.2.1 Choices of vibrator arrangement

Based on the intensity and frequency of acoustic signals, vibrators in a multichannel device can carry information in two ways. First, each vibrator can carry a different section from the speech spectral shape (intensity or frequency). This means they are all similar in carrying a certain physical property of sound. Second, the vibrators do not carry similar acoustic information *e.g.* some carry intensity information and some spectral information. The first will be referred to as similar function multi-location stimuli (SMLS) while the second referred to as different function multi-location stimulation (DMLS).

Similar function multi-location stimulation (SMLS)

One variation of SMLS are devices simultaneously encoding the spectral information of speech to the place of vibration on the skin and its amplitude to intensity of displacement. This is achieved by allocating different vibrators to different frequency bands of speech. The displacement amplitude of each vibrator normally is a gradient function of the energy in speech signal frequency bands, where stimulation frequency is often a fixed frequency. The vibrators can be arranged in any format on the skin *e.g.* in line or as clusters, but in all cases they would be classified as SMLS. A device used by Gault and Crane (1928) in which five vibrators carry band-pass information from speech to the fingers of one hand is an early example of an SMLS device. Another example is the Queen's University vibrotactile vocoder that uses clusters of vibrators, each carrying similar information (the amplitude of each vibrator is controlled by a band-pass signal of speech). Other examples of SMLS device are the 23-channel vibrator by Engelmann and Rosov (1975) and the two-channel device by Spens *et al.* (1996). For further examples see Section 2.3.1 and Mason and Frost (1992).

SMLS designs in which the vibrators are placed in a single row on the skin are referred to as uni-dimensional designs (Reed *et al.*, 1982). It should be noted that they are uni-dimensional in respect to the surface of the skin, and in fact the same configuration may have a two-dimensional encoding (displacement of a single vibrator and number of vibrators).

Different function multi-location stimulation (DMLS)

In a DMLS device, the relative position of vibrators in respect to each other is important and the nature of information carried by each vibrator varies. The "time swept" and "frequency and intensity to place" devices are two examples of DMLS. In most DMLS devices, vibrators vibrate at some constant intensity.

Frequency and amplitude to place

This is when the spectral shape is presented by one row of vibrators and intensity in other rows. Configurations of the Optacon (24×6 vibrotactile matrix) used by Snyder *et al.* (1982) and Yeni-Komshian *et al.* (1977) are examples of DMLS. In the study of Yeni-Komshian *et al.* (1977) 18 of 24 columns were utilized to signal centre frequencies between 250 to 7700Hz and the 6 vibrators in a row were quantised in 5dB steps of intensity.

Time swept

Another variation in DMLS is to use multiple rows to represent time (a kind of memory) while presenting spectral shape in each row. In this type of design known as "swept time", the signals to a row of vibrators moves into the next row after a pre-set interval. The notion for this design apparently stemmed from the fact that it is more difficult to distinguish short stimuli (see Chapter 3). Examples of this design are devices by Ifukube (1982) and Kirman (1974). The preliminary evaluation of a time swept device by Ifukube (1982) showed that in practice the pattern becomes complicated because of the movement by scanning in addition to that of the progressive change of speech spectrum.
More examples of these two different classes of vibrator can be found in Mason and Frost (1992), Sherrick (1984) and Reed *et al.* (1982).

2.2.2 Choices of information

For any of the described possible arrangements regardless of being single or multi-location, a single vibrator can be a carrier of various types of information from speech. Followings are examples of some of the more common choices of information to extract from sound (speech and non-speech) for tactile stimulation.

Direct speech signals

This is the simplest approach where acoustic signals are presented directly to the skin without being modified in anyway. Numerous designs were made and evaluated by using this approach. The usefulness of the approach has been proven and even today is supported by many researchers. For citation of these works, see Summers (1992), Mason and Frost (1992). A recent example of such an approach is the work by Plant *et al.* (2000).

Amplitude envelope

Amplitude envelope is known to convey at least a degree of segmental information of speech (Rothenberg, 1979). In this method depending of the number of channels used, the envelope of different frequency bands of speech is extracted and modulated on a fixed frequency carrier most suitable for tactile stimulation. The Queen's university tactile vocoder is an example of such a device. In this device envelopes are extracted from 16 band-pass filters and used to amplitude-modulate a 100Hz square wave carrier to drive the solenoids. Other examples of devices extracting amplitude envelope are; Tactaid II (see Galvin, 1999), Engelmann and Rosov device (1975), earmold sound to tactile aid by Weisenberger *et al.* (1987) and single-channel Minivib3 (Cholewiak *et al.*, 1986; Weisenberger *et al.*, 1991).

Voice fundamental frequency

Following experiments showing the importance of information carried by voice fundamental frequency in hearing (Rosen *et al.*, 1981; Boothroyd and Hnath, 1988), designs were developed to convey similar information tactually. Devices used by Rothenberg and Molitor (1979), Boothroyd and Hnath (1986) and Boothroyd and Hnath (1988b) and Portapitch (used by Waldstein and Boothroyd, 1995) are examples of tactile devices using voice fundamental frequency.

2.2.3 Choices of vibrator

Three different types of vibrators have been used in mechanical stimulation of skin: electromechanical, air jet and liquid.

Electro-mechanical stimulators

These are by far the most commonly used vibrators in tactile devices. Various designs can be found in Cholewiak and Wollowitz (1992). In general, electromechanical devices are driven either by electromagnetic or by piezo-electric force. Each offers certain advantages to the other in terms of the mechanical power, energy efficiency, frequency response and size.

Air jet stimulators

Stimulating the skin with airflow is another alternative for mechanical stimulation of the skin. Hill (1970) describes the advantages of the air jet compared to conventional electromechanical stimulation in being able to produce a relatively uniform stimulation over a non-uniform cutaneous surface. Hill's display consists of five air jets, each formed by a 0.031 inch outlet nozzle under control of a high-speed electromagnetic valve. The air-pressure pulse, measured 1/8 inch directly above the air-jet outlet, is about 1psi, with a rise/fall time of above 0.5ms. The repetition rate was fixed to 160Hz.

Liquid stimulators

An alternative method for applying vibrations to skin is the use of travelling waves in liquid. An example of such a device is the design by Békésy (1955) which consists of a 30cm brass tube with a constant width slit along its length. Around a brass tube, a plastic mantle was cast, forming a membrane along the slit so that its thickness and its elasticity varies along the length of the tube (10:1). A rim perpendicularly mounted on the membrane provided the resting point for the arm of the subject. The tube was filled with a fluid and the fluid was vibrated by means of a rod, mounted perpendicular to the brass tube on the stiffest side of the membrane. This device, originally designed as a model of cochlea, was later tested with speech materials.

Electromagnetic vibrators have attracted more attention than air and liquid vibrators due to the fact that they can produce much more complex vibratory patterns than air and liquid vibrators. Examples of electromagnetic matrices that theoretically have the capability of generating high intensity vibratory patterns are designs by Shinohara *et al.* (1998) and Craig and Summers (2000). While the first utilises miniature electromotor design, driving a matrix comprised of 64×64 vibrating elements in an area of 200×170mm, the latter uses the piezo-electric force, incorporating a 10×10 matrix of actuators into an area of $10mm^2$.

2.3 Do multi-channel devices perform better than single-channel devices?

There are two approaches to answer this question: 1) to compare the performances of one device with another known device; 2) to compare the rate of learning of a subject in acquiring new materials by each device.

2.3.1 Comparing the performances

Performance of a given device can be estimated in two ways: a) to compare the device with evaluation available from other devices; b) to conduct a study to compare two devices simultaneously.

The first approach provides large number of studies, which differ in their test materials and experimental conditions. The second approach has the advantage that the two devices are at least compared under relatively equal conditions. Following are examples from simultaneous comparison of two devices.

1- Spens (1980) compared 8 different tactile systems, three systems (single and multi-channel) stimulating the fingertips and five systems stimulating the areas from the posterior sides of hips to chest on a single subject. Testing by closed-set word recognition for a single subject, he concludes methods using more stimulators were better than those using a single vibrator. However, his data suggests that there is no consistent relationship between the number of vibrators and improvement in performance (the only measure being the identification of the Swedish numerals).

2- Carney and Beachler (1986) tested the validity of Spens' results for suprasegmental aspects of speech and addressed issue of subject variability. They compared the recognition of three supra-segmental aspects of speech (number of syllables, stress pattern, intonation pattern) through a single-channel and a SMLS multi-channel device.

The multi-channel device was a 24-channel tactual vocoder (designed by Engelmann and Rosov, 1975), composed of 24 one-third-octave filters, covering speech in the frequency range of 80-10,000Hz. The vibrators oscillated at a constant frequency of 60Hz and their vibration excursion was proportional to the amplitude of the incoming signal *i.e.* higher intensity stimuli result in larger excursions. The single channel device was a (Siemens) Fonator with a similar intensity-coding scheme. Note that Carney and Beachler's description of the multi-channel device is slightly different from that of Engelmann and Rosov. Engelmann and Rosov describe the device as a 23-channel vocoder, 15 channels are divided logarithmically covering the speech frequency range between 200-4000Hz and an additional four channels on each side of this range cover speech in the frequency range between 85-200Hz and 4-10 kHz respectively.

These two devices were different in their testing site. The single channel (Fonator) was tested on a finger of one hand while the multi-channel device was tested with a half of the vibrators on the lower arm and the other half above the elbow. While the report does not give any details regarding the contactors, it specifies that the performance of the single channel device was significantly better on the syllable-number and syllabic stress tasks and that no difference was found for the perception of intonation.

3- Boothroyd and Hnath (1986) reported a similar conclusion from the comparison of a single and an SMLS multi-channel device. They used 8 channels, covering speech over the frequency range 80-350Hz. Only one vibrator could vibrate at a time. Neither of the different type of tactile display in this study performed better than the other. It is worth mentioning that Watson *et al.* (1991) refers to the results of this research as an atypical result.

4- Carney (1988) extended her earlier work to recognition of consonant and vowel stimuli by using the same single and multi-channel device used in 1986. Carney reports that both selected single and multi-channel devices perform similarly in transmitting the feature of voicing, manner and place of articulation and that the preservation of the envelope of speech is not necessary for transmission of segmental features of speech.

5- One of the most recent studies comparing the performance of a single and a multi-channel device, which presents more details of the experiment, is by Eberhardt and Bernstein (1990). The single-channel device was evaluated under three conditions. Two conditions involved scaled and shifted glottal pulses (F_0) to pulse rate ranges suited to tactual sensing capabilities, and the third transformed F_0 to differential amplitude of two fixed-frequency sine waves. The multi-channel device provided indication of F_0 on one channel and high-frequency speech energy on the other. All vibrations except the second channel of the multi-channel device was applied through a contactor of $0.28cm^2$ (*i.e.* CD=3mm, SD=3.2mm) to one hand while the second channel was applied by a small vibrator held by subjects in their other hand. They report that all single-channel methods significantly improved speechreading with no difference in performances among them. The rather puzzling point was that the performance of the multi-channel device, which had an additional high frequency supplement compared to the single channel device (in a remote site) negatively affected the performance of the single channel.

6- In 1991 Weisenberger *et al.* reported another study to estimate the difference between the performance of single and multi-channel devices. A major difference between this study and the Carney (1988) study was that both single and multi channel devices were evaluated on the same subject. This precaution was expected to minimise any inter-subject differences that might affect performances.

The selected single-channel vibrotactile devices were the Minifonator (by Siemens Hearing Instruments) and AB Special instrument Minivib3. The Minifonator uses broadband signal processing applied to a contactor area of 2.5cm^2 on the dorsal side of the left wrist. The second single-channel device, Minivib3, was also worn in a similar location during test. Unlike the Minifonator, Minivib3, has a rectangular vibrator with dimensions of 6.5×4.3×1.7cm. Unfortunately, little is known regarding the contactor area of this device or the signal processing of the first single-channel device. The signal processing stage of the Minivib3 is based on extracting the envelope of the acoustic waveform and using this to amplitude modulate a 250Hz carrier.

The performance of the two single-channel devices were compared with a multi-channel Queen's University vibrotactile vocoder developed at the Central Institute for the Deaf. The Queen's University device was composed of 16 one-third-octave filters (except for the lower two which are two-thirds octave wide) with centre frequencies between 140-6350Hz. This device, similar to the Minivib3, extracts envelope information from each of these filters to modulate the amplitude of a 100Hz square-wave. Unfortunately nothing regarding the area of the vibrator is mentioned in the technical notes nor other sources quoted for reference (*i.e.* Engeretson, 1986; Scilley, 1980). The distance between vibrators was 10mm centre-to-centre.

Weisenberger *et al.* (1991) found that the multi-channel aid provided more information to the wearer compared to the single channel devices. The superior performance of the multi-channel device was mostly in tasks requiring phoneme recognition. The two classes of device performed comparably in tasks requiring the perception of amplitude envelope characteristics such as syllable rhythm and stress.

7- Reed and Delhorne (1995) also evaluated subjects using the Tactaid II+ and the Tactaid 7. Tactaid II+ is a device with two vibrators worn on the wrist while Tactaid 7 is a device with seven vibrators often worn on the sternum or the abdomen. The Tactaid 7 is designed to provide more spectral information than the Tactaid II+ and its processing scheme allows only two vibrators to be active at any given time. In their study, seven adults used the Tactaid 7 daily for between 2 and 4 years. For two subjects, the benefit demonstrated with the Tactaid II+ was slightly greater than that shown with the Tactaid 7.

8- Waldstein and Boothroyd (1995) compared the performance of the 16 channel Portapitch with a single-channel device. Both devices were driven by voice F_0 information. The multi-channel device covered the full range of the speaker's fundamental frequency with the channel number being proportionally related to the logarithm of F_0. The single channel device converted the F_0 to a vertical finger displacing device that, unlike a conventional vibrator, was providing information through a mixture of proprioceptive, pressure, and displacement receptors. Waldstein and Boothroyd report neither of the F_0 displays was better than the other one.

9- Galvin *et al.* (1999) compared two multi-channel devices. One of the devices was Tactaid II+ and the second was Tactaid 7. Details of devices have been previously explained in the work by Reed and Delhorne (example number 7). Subjects were eight adults with hearing impairment who used one device for approximately 10 weeks. Their results show no consistent advantage for either device over the other.

For more evidence on the poor performance from multi-channel devices see Waldstein and Boothroyd *et al.* (1995), Summers (1992), Weisenberger (1989), Weisenberger *et al.* (1978).

2.3.2 Learning progress

Another factor that is appropriate to be considered as an index of performance is the rate of learning (improvement in vocabulary). Similar to the reason given earlier, it will be more informative if such a conclusion can be drawn from studies that simultaneously compare a single channel device with a multi-channel device rather than those evaluating a single device.

An example of such a comparative study is given by the work of Carney (1988), as described earlier. The testing materials consist of both consonants and vowels. This study demonstrates that the learning curve for the users of multi channel devices is flatter. Boothroyd and Hnath (1988b) also reports that the effect of the supplement through a 16 channel device reached a plateau after about 13 to 14 hours of training.

2.4 Conclusion

This chapter presented an overview of vibrotactile devices, based on their function. However, it was unable to establish which of the major design approaches for tactile prosthesis performs better than others. The review shows that while some studies indicated better performance for the multi-channel device, the effect even can be negative. It is known that considerable differences in the procedure followed in each study is partly responsible for the observed differences (see Weisenberger, 1991; Eberhardt and Bernstein, 1990; Alcantara *et al.*, 1990; Reed *et al.,* 1982).

The presented review conveys two general points.

- Tactile devices, regardless of their number of channels or signal processing strategies, can be useful as adjuncts to speech communication (Brooks *et al.,* 1986-- see also, Weisenberger and Miller, 1987; Reed *et al.,* 1982).

- The information transmission rate through a vibrotactile device does not increase proportionally with the number of stimulators.

The next chapter will look at the behaviour of the second part of the vibrotactile system – the human – in an attempt to understand the reasons for the wide differences among reports from different authors and to find the underlying mechanism for the failure to obtain significant advantages from multichannel devices.

CHAPTER 3

FROM VIBRATIONS TO PERCEPTION

3.1 Introduction

In this chapter, we follow a vibratory signal from the surface of skin to higher cortical areas, in an attempt to understand the human vibratory sensory system. This is crucial in the design of any vibrotactile device aimed to use the maximum capability of this sense. Furthermore, we try to understand the limited benefit observed in the application of tactile devices described in the previous chapter.

Two approaches are taken in this endeavour namely the "stimulus and response" and the "purely physical view" (Figure 3.1). Though different, these complement each other in gaining as complete an understanding of the human tactile sense as possible.

3.2 Stimulus and response

One way to characterise the behaviour of a system is to expose the system to different inputs and observe the outputs. Where the system is human, this type of test is most commonly referred to as a "psychophysical test". Psychophysical studies are the foundation for understanding the vibrotactile sense and concern the relationship between the physical properties of the stimulation and the arisen subjective sensation. During vibrotactile psychophysical tests, the parameters related to the input stimulus (*i.e.* signal properties) and the position of stimulus on the surface of body may be varied.

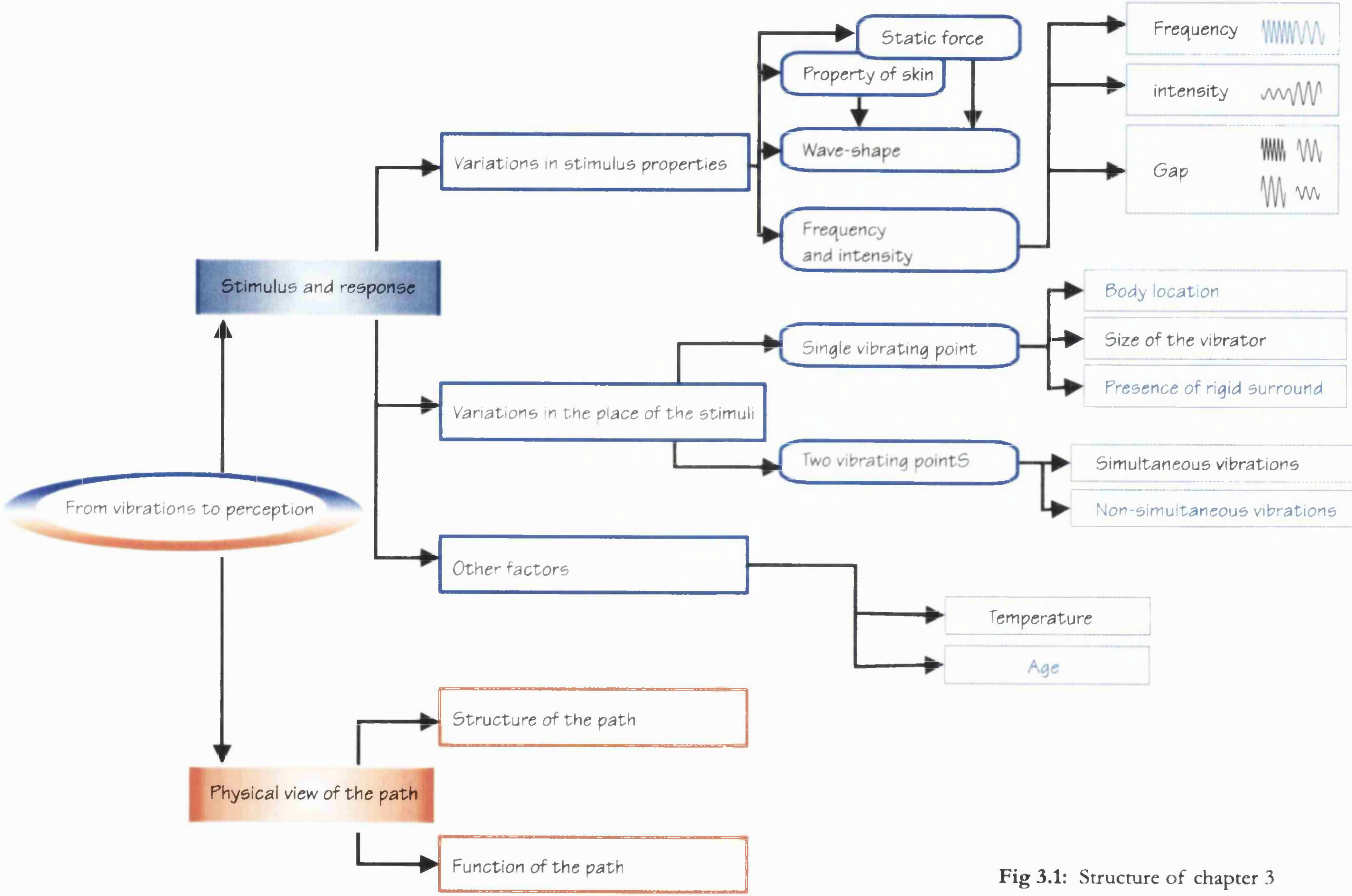


Fig 3.1: Structure of chapter 3

3.2.1 Variations in stimulus properties

Vibratory (input) signals may vary in their shape, frequency and intensity. The shape and intensity of the applied wave is affected at the surface of skin by a change in parameters such as static force and further on at the receptor level by the properties of the skin layers.

The frequency limits of the tactile sense (tactile area) were among the first parameters investigated. By applying simple harmonic motion perpendicular to the skin, it is found that the tactile sense has a bandwidth of about 1-700Hz (Rothenberg *et al.,* 1977; Bolanowski, 1988). Over this 700Hz band, the tactile sense has a dynamic range of sensitivity of about 40-55dB (Spens *et al.*, 1996; Verrillo *et al.*, 1992; Békésy, 1955), where the highest boundary of intensity is limited by the threshold of pain. The perceived vibratory sensation varies with frequency, those lower than 15Hz are felt as gentle impacts, fusing together to cause a tingling sensation at frequencies of higher than about 18Hz (Knudsen, 1928). Later, investigations have revealed that the detection threshold for this range of frequencies is affected by two signal-related parameters, which are the wave-shape and the initial static force between the skin and the vibrator.

Wave-shape

The effect of wave-shape was investigated by Rothenberg *et al.* (1977). They applied two sets of signals to the skin, almost equal in all respects except their rise/fall time (see Figure 3.2). While the measured detection threshold for a Gaussian shaped signal changed as a function of the pulse width, it remained constant for a flat-topped signal (f=20 to 500Hz, SD=8mm, CD=6mm, ID=1mm). In mechanical terms, the difference between these signals is in their acceleration. Later experiments also suggest (at least for frequencies around 200Hz) that acceleration is the critical stimulus property for activating tactile receptors (Horch, 1991; see also Lamoré and Keemink, 1988).

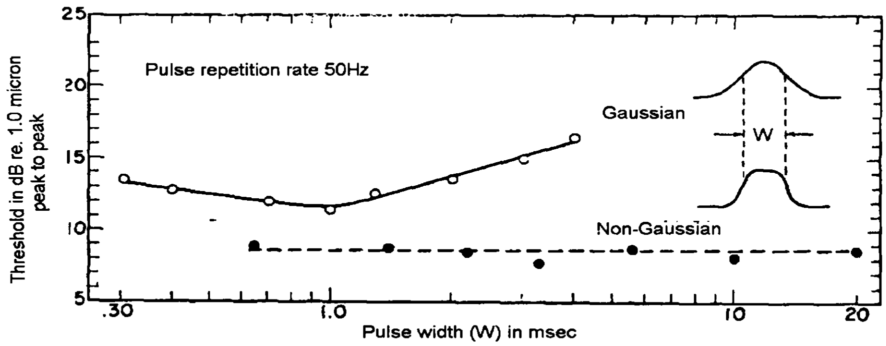


Fig 3.2: The effect of the shape of the stimuli on perceived threshold measured at thenar eminence. Modified from Rothenberg *et al.* 1977

Static force

What happens if the space between the vibrator and the tactile receptor is altered? Numerous terms in the literature *i.e.* static force (Franzén and Nordmark, 1975), contactor height (Lamoré and Keemink, 1988) and initial indentation (Gescheider, 1990), refer to this setting between vibrator and the tactile receptor. Variations in this setting appear to have an effect on the detection threshold similar to that caused by a change in wave-shape. For instance the data from Lamoré and Keemink (1988) presented in Figure 3.3 (left) suggests that as the contactor height is reduced (*i.e.* the space between the vibrator and skin is increased), the threshold reaches a steady level for test frequencies of 5-500Hz. Lamoré and Keemink suggested that this constant threshold might be determined by a separate receptor system.

The following model appears to explain the observed similarity between the change in static-force and the wave-shape (Figure 3.3 B). Consider the case in which a space (L) exists between the moving object (VO) and the medium (Vt), with the receptor (R) residing within the medium. If (VO) is displaced with a sinusoidal transversal motion so its X co-ordinate remains constant (vibrator waves on Figure 3.3 B), the recorded wave-shape by the receptor (R) is a function of the spacing (L). Alteration to the L distance creates jerk (first derivative of acceleration) to the motion of R and subsequently affects its acceleration at the time intervals following the collision (physical contact).

This can be demonstrated mathematically as follows:

Let the transverse speed be v_y and the transverse acceleration, a_y. The constant (A) is the wave amplitude and ω and ϕ are the angular frequency and phase shift respectively.

$$\begin{cases} v_y = \dfrac{dy}{dt} = -\omega A\cos(\phi - \omega t) \\ a_y = \dfrac{dv_y}{dt} = -\omega^2 A\sin(\phi - \omega t) \end{cases}$$

The maximum values for v_y and a_y are the absolute values of the coefficients of the cosine and sine functions:

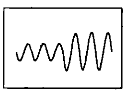
$$\begin{cases} (v_y)_{Max.} = \omega A \\ (a_y)_{Max.} = \omega^2 A \end{cases}$$

Therefore, the speed of point P reaches its maximum value (ωA) when y= 0 and has its maximum acceleration (ω^2A) when y= ±A, each changing sinusoidally between these extremes. Thus, the acceleration at the time intervals following collision depends on L and the maximum amplitude of the applied signal. Recall that acceleration was a determining factor in accounting for the change in the threshold with wave-shape.

Frequency and intensity

Results obtained from variations in vibrating intensity of a single point

The just detectable intensity difference is conventionally defined as one half the difference between the intensity of a stimulus, which is called "greater" than a reference stimulus 75% of the time and that which is called "smaller" 75% of the time (Sherrick and Cholewiak, 1986). The measured detectable intensity difference is also referred to as the Intensity Difference Limen (DLI), Intensity Differential



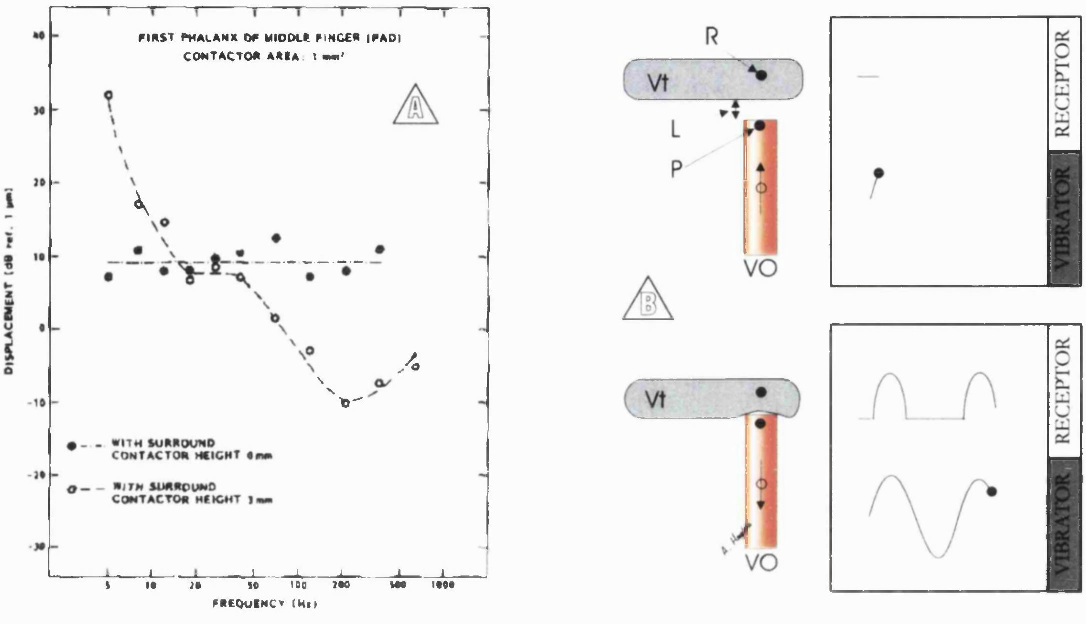


Fig 3.3: With the small vibrator as the distance between the vibrator and skin increased the absolute threshold reaches a steady level along the tested frequency range (graph A- modified from Lamoré and Keemink (1988). Illustration of the impact caused by sinusoidal oscillation, before impact (B-top) and after almost one and half cycles of wave (B-bottom). Note alteration in the shape of the signal received at a point (R) within (VT).

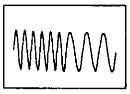
When the DLI is measured by changing the intensity of an ongoing vibration, the method is called a Continuous Pedestal Method. This method was implemented in some of the older studies (Gescheider *et al.,* 1990). An example of such an estimate is the measurement by Knudsen (1928). He reports the DLI of about 0.4dB, which was inversely intensity dependent and independent of frequency.

Gescheider *et al.* (1990) used the Continuous Pedestal Method to obtain the value of 1dB for DLI, increasing to 1.5dB when the intensity decreases from 40 to 20dB SL. At lower than 20dB SL the DLIs rise sharply to about 2.5dB as the amplitude of the pedestal gets closer to the threshold (4dB SL).

A comparison of DLI values obtained from different measuring methods suggests that the Continuous Pedestal Method gives the lowest estimate for DLI (for similar result in hearing see Pickles, 1988). However, subsequent experiments on the effect of two successive waves on each other (see below) cast doubt on the accuracy of the DLI found from the Continuous Pedestal Method.

Results obtained from variations in frequency of a single vibrating point

A perceived change in frequency of a continuous signal provides information regarding how the perceptual system can resolve two frequencies in time.



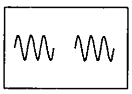
Study of perceived change in frequency of a continuous signal is one of the methods practised to establish the value of DLF (DLF is defined in the same manner as DLI) and the values provided by using this method is known as *frequency discrimination* (Pickles, 1988).

The "warble tone method" is a method to measure the frequency discrimination in which the frequency of the stimulus varies to higher and lower than a reference value (Rothenberg *et al.*, 1977). In purely physical terms, the warble tone method measures the sensitivity to a frequency modulated (FM) stimulus.

Rothenberg *et al.* (1977) used warble tone method to measure the DLF of the tactile sense at frequencies between 10-250Hz. They found that the values of DLF were dependent on the wave-shape particularly at higher frequencies. For both sinusoidal waveforms and Gaussian pulses with a constant width of 1ms, the DLF values were about 45% at 10Hz. This Reduced to 9% for sinusoidal waveform and to 21% for Gaussian pulses as the frequency approached 250Hz. (Site forearm, CD = 6mm, SD = 8mm, ID = 1mm).

Results obtained from inserting a gap within the signal

Two bursts of mechanical stimulus separated by an inter-stimulus interval



(ISI) can be used to investigate their temporal affect *i.e.* the way two stimuli affect each other in time and to establish the DLI and DLF values of the tactile sense.

Temporal effect of two successive stimuli

A double burst stimulus can produce a different overall sensation (summation) and affect the perceived strengths of one another.

The concept of this type of test originally stemmed from research in hearing. When Zwislocki and Sokolich (1974) conducted a series of experiments with

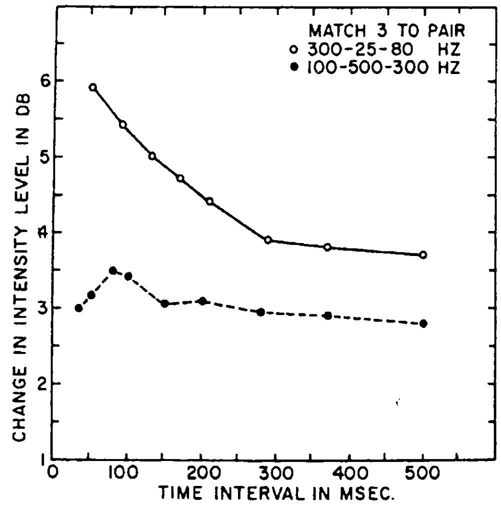
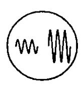


Fig 3.4: Perceived change in the overall intensity (summation) of two successive burst as a function of ISI. Vibration frequencies are indicated on the graph. (From Verrillo, 1975)

two successive separate bursts of a monotic signal (in one ear), they found the presence of two fundamentally different subjective responses. Zwislocki and Sokolich named these two responses Summation and Enhancement. Summation is when the subject reports the overall strangthloudness of two successive signals. Enhancement is when the subject reports the loudness of the second burst of a signal preceded by another burst of a signal. Enhancement and summation, though both resulting in an increase of strangthloudness of two successive stimuli, are differently affected by manipulation of time and frequency.

Verrillo and Gescheider (1975) examined summation in the tactile sense and reported very similar results to those found in hearing. In general, within the high frequency range, 100-500Hz, subjects found it much easier to respond to summation when the comparison stimulus was at the same frequency as the second stimulus. Verrillo and Gescheider stated that the summation process observed at a supra-threshold level was different from that observed at threshold. Tactile summation at supra-threshold level is independent of the time interval between the two stimuli up to 500ms, whereas summation at threshold has a time constant of 200ms. When the frequencies of the two bursts were far apart (25-300Hz), the results show that summation still exists. Figure 3.4 shows that the recorded 6dB change in intensity from summation of two widely different frequencies corresponds to a doubling of sensation magnitude. The 3dB effect obtained when the two stimuli were close in frequency implies the sensation magnitude is summed (Verrillo and Gescheider, 1975; Verrillo, 1980).

Two successive bursts of stimuli can also affect the perceived strength of one



another. The sensation magnitude of a second stimulus is not appreciably affected by the first, when the two stimuli are equal in their sensation strength (Verrillo and Gescheider, 1975). However, its sensation magnitude is affected if the strangthies are different.

A preceding stimulus can enhance the perceived intensity of a following stimulus (forward enhancement). The enhancement effect is observed at inter-stimulus intervals between 75 and 500ms (Verrillo and Gescheider, 1979) and takes place only when the frequencies of the two stimuli are within the same established frequency band of tactile receptors *e.g.* when both stimuli are 25Hz or 300Hz. When the frequencies were selected to be far apart from one another (25-300Hz), the enhancement effect disappears at all time intervals (Verrillo and Gescheider, 1975).

The second psychophysical phenomenon based on the same test procedure, that is detection of the change in the perceived strength of the second signal (burst) from a first burst (ISI < 500ms), is known as forward masking. The term "forward" implies that the detection threshold for the second burst is raised (masked) by the presence of the first burst. Masking fundamentally reflects the same property of the tactile sense as summation. In a summation experiment, the subject is asked to detect the overall magnitude of two almost similar and successive signals. In a masking experiment, the subject is requested to increase the level of the second signal (test) to a detectable level in the presence of another signal (masker). This similarity is illustrated more clearly in Figure 3.5.

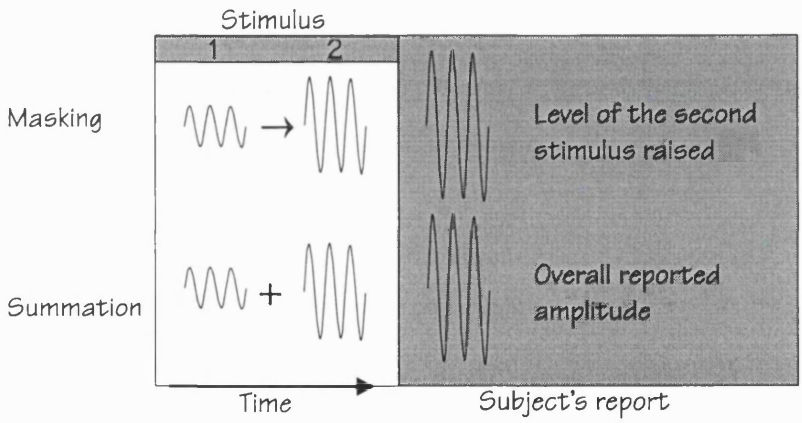
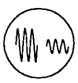


Fig 3.5: Similarity between the masking and summation experiments in an imaginary linear system.

Gescheider *et al.* (1982a) conducted a series of masking experiments and reported that at intensities slightly higher than threshold to about 30dB SL, masking occurs most clearly when the two bursts (masker and test) are close in frequency. Their results also show that a high frequency masker can mask the detection of low-frequency stimuli if the masker is intense enough.

Geschieder (1995) examined the effect of the intensity and duration of the first (masking) burst on the second (test) signal within the set ISI of 25ms. He reported that both increasing the intensity and the duration of the masker raises the detection threshold of the second burst when both signals were at low frequencies (20Hz) or both at high frequencies (250Hz). The effect of duration was more prominent when the duration of the first burst was less than 300ms. Above 300ms, the change in duration has little effect on the perceived strength of the second signal (CD =1.95cm, SD= 2.95cm, ID = 0.5mm, temp. = 30.0 ± 0.5°C).

In some circumstances, a stimulus can affect the perceived strength of a subsequent stimulus even when the ISI is greater than 500ms. When the duration of the first stimulus is increased (to about 16s), the first stimulus affects the detection threshold of the second stimulus, the phenomenon known as "adaptation". Goble and Hollins (1993) show that at a frequency of 25Hz, adaptation can impair or enhance the detection threshold of the second stimulus. When the intensity of the second stimulus is close to threshold, adaptation impairs its detection at a rate of 6-7dB for every 10dB increase in intensity of the first (adapting stimulus). When the intensity of the second stimulus is both higher than threshold and close to the amplitude of the first stimulus, the adaptation improves the amplitude difference threshold (first stimulus duration = 16s, second stimulus duration = 1s, ISI = 1s, f = 25Hz, CD = 5mm, SD = 7mm, ID = 0.5mm, temp. = 32 ± 1°C)



As the perceived strength of a second burst of stimulus is affected by its preceding stimulus, so the perceived strength of the preceding stimulus itself may be affected by the second stimulus. Backward (as opposed to forward) enhancement is an example of such an effect and was demonstrated in tactile sense by Verrillo and Gescheider (1979). In backward enhancement, the subject is presented with two consecutive bursts of signals with the interval less than 500ms. The perceived change in intensity of the first stimulus is then evaluated by the subject. This is done by comparing the stimulus with another of known intensity which itself is presented at a time interval of more than 700ms.Verrillo and Gescheider (1979) found that perceived strength change during backward enhancement is smaller than forward enhancement and can only be observed within 75-200ms inter-stimulus intervals compared to the 75-500ms time interval over which forward enhancement takes place. Backward enhancement was only observed when burst frequencies were similar.

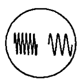
Estimate of DLI and DLF

Two successive bursts of stimuli may also be employed to estimate the DLI and DLF of the tactile sense. It appears that in such a procedure the value of ISI is always set to be longer than 500ms.

When this method is used to measure DLI, it is known as the Gated Pedestal Method. The Gated Pedestal Method has been used widely in recent tactile studies (Gescheider *et al.,* 1990). Fucci *et al.* (1982) applied what appeared to be the Gated Pedestal Method on the tongue and reported values for the DLI which were both intensity and frequency dependent ranging from 0.4 to 1.9dB. Their work appears to lack some details such as the unit for applied physical force, magnitude of the steps used and error range. It suggests that tactile or strictly speaking "lingual" DLI is both frequency and intensity dependent. Their lowest reported DLI value is for 250Hz and highest for 125Hz (CD = 4mm; f = 125, 250, 400Hz; ID = 1mm; no surround).

Gescheider *et al.* (1990) measured the DLI by applying the Gated Pedestal Method and reported values which were essentially very similar to those obtained by applying the Continuous Pedestal Method. They reported the value of 1dB for DLI at 40dB SL raising linearly to 2dB as the intensity declined to 20dB SL (compared to the Continuous Method these values are about 0.5dB higher). The difference between the DLI obtained using these two measuring methods was greater for intensities between 5 and 20dB SL. The Gated Pedestal Method gives an almost constant 2dB DLI for this range, compared to a variation of about 1dB for the DLI recorded for the same range by the Continuous Pedestal Method. (f = noise, 25, 250Hz; CD=19.2; SD=20.2). The reported DLI values of about 1-2.5dB by Spens *et al.* (1996) are also comparable to the values of the two methods reported earlier.

In general, it appears that DLI is frequency independent in the tactile sense as it is in hearing and the values obtained by Gated Pedestal Method are larger than those obtained by Continuous Pedestal Method at intensities over 20dB SL (Turner *et al*, 1989; Gescheider *et al.*, 1990).



It is shown that the insertion of a gap in a continuous signal with two different intensities causes a change in the value of DLI. Thus, it might be expected that the insertion of a gap between two sections of a continuous signal with different frequencies may result in a change of DLF value.

Goff (1967) conducted this experiment with a 2s gap. He reported a DLF value of over 60Hz for frequencies of 200Hz, which is equivalent to 30%. Goff's result shows that the DLFs are inversely dependent on intensity. (f = 25, 50, 100, 150, 200Hz; CD = 6.5mm; SD = 19mm; SF = 8g).

Rothenberg *et al.* (1977) reported a value of 10% for the DLF at a frequency of 25Hz, which in general rises to 35% as the frequency approaches 300Hz. (ISI = unclear, perhaps 2s; site forearm; CD = 6mm; SD = 8mm; ID = 1mm).

There are also experiments showing a lower value for DLF. An example is the work by Franzén and Nordmark (1975). They reported a DLF value as low as 3%. Certain methodological issues make their report less reliable. It appears that they assumed equal sensation contours at various intensities and adjusted the intensity of the test to 30dB SL at each pulse rate. Furthermore, it seems that there is no indication of the frequency response of the vibrator and the displacement-measuring instrument used, to provide an estimate of the real shape of the vibratory stimulus applied. Their description regarding the shape of the applied pulse in the frequency range of 1-348Hz, also does not seem clear (CD = unclear, perhaps 2mm, no surround, ID = 0.5mm).

The result of change in the form of stimulus can be summarised as follow:

- Acceleration is an important factor in determining vibrotactile thresholds
- A short stimulus burst (<2s) affects the perceived strength of a preceding burst in time intervals between 75-500ms.
- A short stimulus burst (<2s) affects the perceived strength of a succeeding short burst in time intervals of 75-200ms.
- A 25Hz burst can still affect its succeeding stimulus at an ISI of >500s if the preceding stimulus is long (on the order of 16s). This is known as adaptation.
- The value of DLF for the tactile sense at frequencies of 20-250Hz varies between 9% and 45%. The values show a direct relation with frequency when two stimuli are separated by a gap and inverse relation with frequency when continuous stimuli (warble method) are employed.

3.2.2 Variations in the place of the stimuli

In addition to alterations to signal properties, factors relating to the place of stimulation can also be changed to provide further information about the performance of the human vibrotactile system. In this regard, vibrations can be applied either to one point (single vibrator) or to multiple points on the skin.

Single vibrating point

The physical location where a stimulus is applied to the skin varies by placing the vibrator in different body locations, by varying the size of the vibrator and by introducing a rigid surround.

Body location

The detection threshold to a single vibrator varies across different body sites. Many experiments (most recently by Cholewiak and Collins, 1991) confirm that spatial and temporal resolution is at its best on the hand. It should be noted that the threshold sensitivity map varies for different type of mechanical stimuli. For instance the lips, which are the most sensitive to pressure, rank well below the fingers in vibrotactile sensitivity (Sherrick and Cholewiak, 1986).

Size of the vibrator

The choice of vibrator size affects the shape of the detection threshold graph with frequency. Verrillo and Gescheider (1992) reviews their earlier work (1963) and suggests that with a very large contactor (CD = 2.54cm) and when the area around the vibrator is restricted by the use of a rigid surround, the (displacement) threshold is independent of frequency at low frequencies (25-40Hz). As frequency is increased beyond 40Hz, the threshold reduces at a rate of about 12dB/octave until maximal sensitivity is reached in the range 200-300Hz. When a contactor of a smaller diameter is used, the response remains constant over a wider range of frequencies. However the approach to maximal sensitivity always has a slope of approximately 12dB/octave with the maximum occurring around 250Hz (see Figure 3.6). The threshold becomes independent of frequency when a very small vibrator (CD = 0.12 and CD = 0.08cm) is used. Later Lamoré and Keemink (1988) presented evidence confirming the results of Verrillo (1963) from small vibrators and found that the threshold response at lower frequencies is not quite flat when a medium size (CD = 1.4cm) vibrator is used.

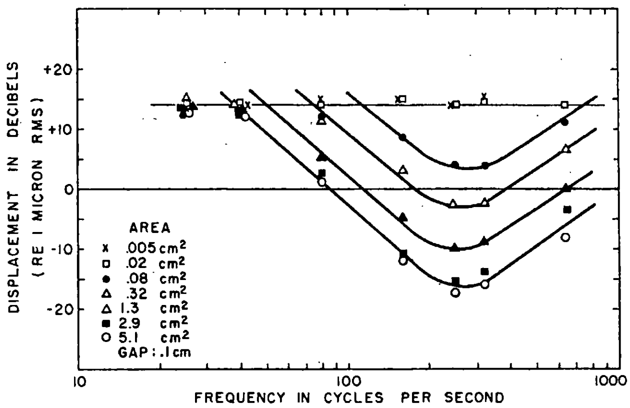


Fig 3.6: Effect of the vibrator's contact area on the vibrotactile threshold (from Verrillo, 1963)

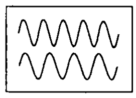
Presence of rigid surround

Most values for absolute thresholds quoted so far were obtained in a situation where the contactor was surrounded by a rigid surround. Gescheider (1978) investigated the effect of a surround on the detection threshold and confirms earlier findings that the removal of a surround introduces a considerable elevation of the detection threshold in the low frequency and cause decrease in detection threshold at high frequencies. His data shows that the definition of low and high frequency is governed by the size of the vibrator (site thenar eminence). Lamoré and Keemink (1988) further studied the effect of the surround on the detection threshold and reported that the decrease in detection threshold at low frequencies is not equal for all frequencies. His data showed that for the case where contactor with the area of 1.5cm (CD=1.4cm) was used the peak of decrease in low frequency detection is at about 18Hz. He also reported that the presence of surround did not equally affect the low and high frequency section of the detection threshold curve at different body sites.

Two vibrating points

The possible combination from two vibrators is higher than what is possible with a single vibrator. Hence, this section is classified into two categories; simultaneous vibrations and non-simultaneous vibrations.

Simultaneous vibrations



Gilson (1969a) investigated the perception of two simultaneous high frequency (both 150Hz) vibrations on the skin. He situated one vibrator (test) on the ventral surface of the thigh while placing the second vibrator (masker) on one of the four ipsilateral or their symmetrical contralateral points. His work led to an important result, the detection threshold for detecting the test signal was raised in presence of the second signal. The rise in the threshold of the test signal (masking effect) does not depend on the distance between the masker and test vibrator or on their relative ipsilateral or contralateral position. Instead, it appeared that the distances of the points from the CNS (central nervous system) play a crucial rule in raising the detection threshold. Gilson found that if the time interval between the two stimulating signals from any location on the skin is chosen according to their distance from the CNS, any two distantly placed vibrating points can raise the detection threshold to the same level as two closely placed stimulating points. However, Gilson did not realise these results are only valid within a certain range of frequencies. It was only in 1977 that Ferrington *et al.* reported that there was no masking when both bursts were within the low frequency range (*i.e.* non- Pacinian receptors – described in Section 3.3). Note that masking was present at both low and high frequencies when two stimuli were applied in succession to a single location.

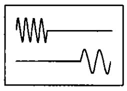
There were some exceptions to Gilson's general rule. When vibrators were on the fingers of the same hand the elevation in threshold was two-fold higher compared to when the vibrators were on the fingers of different hands. Gilson explained that the difference might be due to some fundamental difference in the neural organisation of the sensory system.

Later in 1979, Cholewiak conducted experiments on tactile summation on the ventral surface of the thigh, which is the same body site as Gilson's experiment. It has been previously explained that how masking and summation experiments reflect the same property of tactile sense. He found that the perceived strength of one or more high frequency (100-500Hz) vibrating points with similar intensity appears to be approximately proportional to the number of vibrators used, which was similar to Gilson's findings. Although in Cholewiak (1979) experiment, the vibrators were placed very close to each other (maximum distance = 80mm, CD = 5mm), the possibility of a superposition of stimulus energy from each vibrator in the skin itself was ruled out by the existence of at least six inactive contact points surrounding each vibrator (CD= 5mm).

To summarise, the inverse relation between the size of vibrator and absolute threshold reported by Verrillo (1963), the summation observed with multi-vibrators by (Cholewiak, 1979) and the threshold increase observed during masking experiments by Gilson (1969b), all appear to be related to summation. Note also that the summation from a multi-vibrator (spatial summation) only occurs at frequencies higher than 80Hz (Cholewiak, 1979; Verrillo, 1963) while summation from a single vibrator (temporal summation) persists at lower frequencies (see Figure 3.4)

Non-simultaneous vibrations

Verrillo and Gescheider (1979) examined the effect of a short burst of vibrotactile stimulus (2ms) on preceding and succeeding stimuli when they were applied to ipsilateral locations on the hand. He reported that the presence of the first stimulus both enhanced and suppressed the perceived strength of the second stimulus under certain circumstances. At ISIs between 25-65ms, the presence of the first stimuli caused suppression of its succeeding stimuli. When the ISI was raised to higher values, an enhancement effect appeared with a peak effect at an ISI of about 150ms. (1st CD = 12.8mm, 2nd CD = 19.2mm).



When the experiment was conducted in the backward mode, only the suppression effect was observed no matter what ISI was used. The peak effect was at the shortest ISI used *i.e.* 25ms (Figure 3.7).

Gescheider and Verrillo's (1982b) finding are in general agreement with Verrillo and Gescheider (1979) and confirm that the observed effects appear to be independent of the relative location of the two vibrators (at least on the hand). However, Gescheider and Verrillo report that enhancement and suppression were only observed when both stimuli were in the same frequency channel *i.e.* 25-25 or 300-300Hz. (CD = 19mm, surround of unknown diameter used).

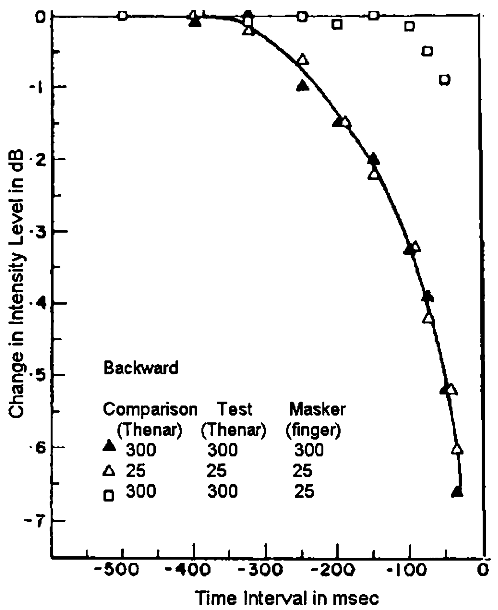


Fig 3.7: Strong backward suppression when two stimuli are within the same frequency channel (adapted from Verrillo, 1979).

3.2.3 Other factors

Body temperature and subject's age, are known to affect the perceived strength of vibrotactile stimuli.

Temperature

Vendrik *et al.* (1958) showed that a change in temperature of certain layers of skin affects the detection threshold of applied stimuli. They heated a 13cm square area on the volar forearm by either microwaves (wavelength of 10cm) or irradiation from a hotplate (infrared). Microwaves can penetrate the skin and increase the temperature almost uniformly (at least to the dept of 2mm) while infrared will increase the temperature in a graded manner with depth. Warming from these two irradiation sources was comparable within about 0.3- 0.5-mm of the skin surface.

Green (1977) studied the effect of temperature on detection threshold at frequencies between 30 to 250Hz and reported that the lowest absolute threshold at 250 and 150Hz occurs at 37°C. Cooling and warming greatly lowers sensitivity at these two frequencies. At lower frequencies the sensitivity is less affected by change in temperature. At 30Hz, both Green (1977) and Bolanowski *et al.* (1982) agree that absolute threshold is independent of skin temperature. The slope of the threshold rise for cooling at 250Hz was slightly higher than 1dB/1°C. (Temp = 20 to 40°C, f = 30, 250Hz – Green; f = 12 to 100Hz - Bolanowski).

Age

Advance in age can raise the threshold of tactile sensitivity. The maximum of the effect can be as much as 20dB at a frequency of about 250Hz (Verrillo and Gescheider, 1992)

3.2.4 Summary of the psychophysical studies

When two successive short bursts of stimuli (<2s) are applied to the same location of the body by a single vibrator, within a time interval of <500ms the following effects are observed:

- Two bursts equal in perceived strength have no appreciable effect on one another.
- Two bursts with different intensity affect the perceived strength of each other as well as their overall perceived strength.
    - Two bursts affect their overall perceived strength regardless of their frequency (summation).
    - Masking experiments show that the duration of the first stimulus has an effect on the perceived strength of the second stimulus. This effect reaches a plateau when the duration of the first stimulus exceeds 300ms.

- Forward enhancement takes place when both stimuli have similar frequencies *i.e.* 300-300 or 25-25Hz.
- The perceived strength of the first stimulus is only weakly affected by the second stimulus, and only when ISI<200ms. (Backward enhancement and suppression)

When two successive short bursts of stimuli (<2s) are applied to different locations of the body within a time interval of <500ms, the following effects are observed:

- At ISI<75ms the stimuli affect the perceived strength of each other regardless of whether they have similar or dissimilar frequencies but to a different extent.

- The first stimulus suppresses the perceived strength of the second stimulus in the time interval of 25<ISI<75ms, and enhances the perceived strength of the second stimulus in the time interval of 75<ISI<500ms.

- The second stimulus only suppresses the perceived strength of the first stimulus at time intervals of 25<ISI<400ms.

- The overall perceived strength of two stimuli (sum) spaced widely on the body appears to be dependent on their relative distances from the CNS. (Gilson, 1969a)

In terms of the relation between single and multi-channel vibrators:
Forward masking takes place both with single and multi vibrators. However, with a single vibrator, forward masking takes place both when the signals are within the same frequency channels *i.e.* 25-25Hz or 250-250Hz (Gescheider *et al.,* 1995a) or across the two frequency channels when the intensities are high

(Gescheider *et al.*, 1982). In the multi vibrator case, forward masking takes place only at high frequencies (Ferrington *et al.*, 1977; Cholewick, 1979; Gilson, 1969b).

Enhancement takes place both with single and multiple stimulators with the following differences:

- For one stimulator, both in forward and backward modes, where the frequency of both stimuli are within the same frequency channel, the forward enhancement takes place when the temporal gap is less than 400ms while backward enhancement only takes place when the temporal gaps is less than 200ms (Verrillo and Gescheider, 1979).
- For a multiple stimulator only in forward mode, when the temporal gap is greater than 70ms and regardless of their relative frequency (Verrillo and Gescheider, 1979).

Suppression is observed (at least on the hand) both in forward and backward multi vibrator mode, forward suppression occurs when the gap is less than 70ms while backward suppression occurs in all intervals.

Summation takes place with both single (Verrillo and Gescheider, 1975) and multi-vibrators (Cholewiak, 1979; Verrillo, 1963) regardless whether the signals are within the same or different frequency channels.

The effect of the ageing on the perceived strength of a vibrotactile stimulus is similar to the effect observed from the reduction of the size of the contactor. The effects observed from these two factors are also similar to the effect of offsetting the temperature from 37°C.

Observations on a similar nature reviewed here have led to the development of the four channel vibrotactile model (see Verrillo, 1963; Verrillo 1966; Mountcastle, 1972; Green, 1977; Gescheider *et al.*, 1982a; Gescheider and Verrillo, 1982b; Capraro *et al.*, 1979; Bolanowski *et al.*, 1988). The response of

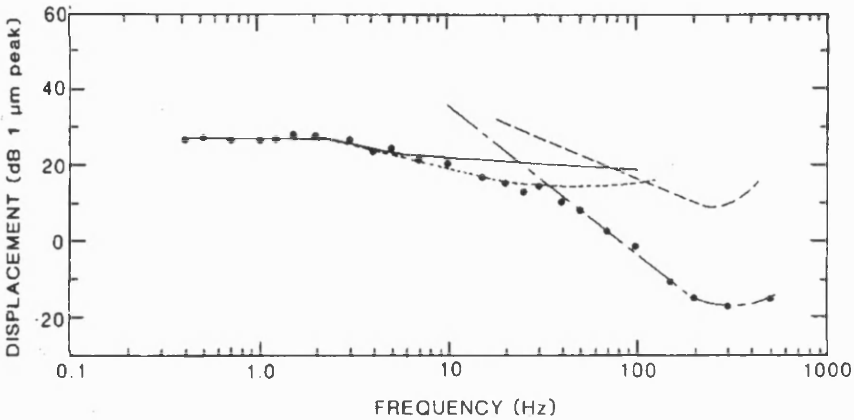


Fig 3.8: frequency characteristics of the four vibrotactile channels (dashed lines) and their overall frequency characteristic (• line). Note that changes in temperature shift these graphs to a different extent. Modified from Bolanowski *et al.*, 1988

these four channels across frequency is presented in Figure 3.8. It should be noted that only three such channels exist in hairy skin (Bolanowski *et al.*, 1994). Table 3.1 shows important characteristics of the tactile sense in comparison to hearing.

Table 3.1: Important characteristics of the tactile sense in comparison to hearing

	Ear	Tactile	Description
Frequency range (Hz)	20 –20000	≈1 -700	Maximum sensitivity near 300Hz
Dynamic range (dB SL)	>115	50 ± 5	Limited by the threshold of pain
DLF	0.3%	9% - 45%	Inversely dependent on intensity
DLI	≈1dB	≈2dB	Independent of frequency

3.3 Physical view of the path

This section looks at the path that a signal initiated by vibration takes from the surface of the skin to higher cortical areas from a perspective of the physical transfer of the signal, involving the anatomy and physiology through which this is achieved.

3.3.1 Structure of the path

Tactile stimuli have to travel through the skin in order to activate the relevant receptors. The skin consists of different layers known as the epidermis, dermis and subcutaneous layers. Each layer appears to posses a different viscoelastic property with an overall non-linear mechanical response (Payne, 1991; Cua *et al.*, 1990; Finlay, 1971). The mechanical property of skin also alters with change in temperature and through ageing (Currier and Nelson, 1992; Sanders, 1973). Tactile receptors, which are a type of mechanoreceptor, are classified into six different types (Guyton, 1996), each with a different size and structure. In general, they appear to follow a simple pattern - the deeper a

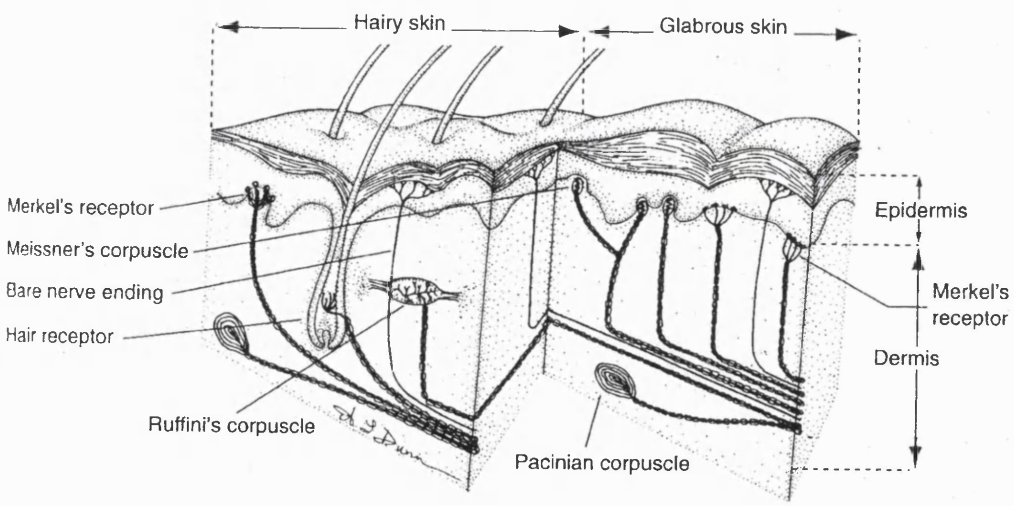


Fig 3.9: Illustration of different tactile receptors and their relative positions within the skin in hairy and non-hairy (glabrous) skin. Adapted from Steward (2000).

receptor resides within the skin, the bigger is the size and the larger is their receptive field (see Figure 3.11). For instance, Pacinian corpuscles are the largest sensory end organ in the body (Carlson, 1998), with a size of approximately 0.5 by 1.0mm housed deep in skin and considered responsible for high frequency sensation up to 800Hz (Guyton, 1996). Free nerve endings are small in size and are found just below the epidermis and around the hair follicles (emergence of shaft and base of hair follicles). At depths between these two types of receptors are at least four different types of tactile receptors - Meissner's Corpuscles, Merkel's discs, hair end organs and Ruffini's end-organs (Figure 3.9).

Vibration signals passing through the skin are expected to be partially filtered by the physical property of the skin, and if adequately intense, will cause receptor potentials. Analogue signals from the receptors are transformed into digital signals and sent as action potentials (AP) along their attached axons. The transformation is in a graded manner such that a stronger stimulus

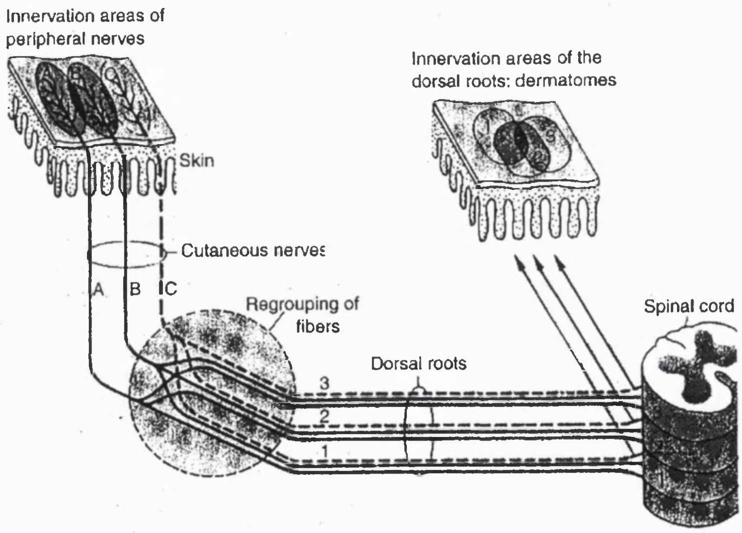


Fig 3.10: Regrouping of ascending cutaneous nerves causes considerable overlap between the innervation areas of different dorsal roots.

produces a greater rate of firing in the nerve. At this level, the reception areas of each nerve are slightly over-lapped (Figure 3.10).

Axons are cells with an internal resistance (cytoplasmic [Rc] + membrane [Rm]) and capacitance. Mostly due to the internal resistance, the propagation velocity of the signal along the axon is a function of its diameter as well as its degree of myelination. The greater the diameter, the faster the propagation velocity.

The axons extend to the spinal cord without any contact or communication between them (*i.e.* without any synapses) and are known as first order neurones. First order neurones regroup along their ascending path. During regrouping, nerves from one group originating from adjacent receptors switch positions with another nerve in a neighbouring group. Regrouping causes considerable overlap of the receptive areas. Note that up to this point, the integration is simple and the response of the first order neurone is either an increase in firing rate when the stimulus occurs within the receptive field or no response at all when the stimulus occurs outside of the receptive field.

Within the next stage of the ascending path of these neurones, two important phenomena take place namely inhibitory and excitatory effects. An excitatory effect is when an ascending neurone takes two or more inputs, one from its own lower order neurones and another a depolarisation input from an inter-neurone that is activated by other neurones. Where the inter-neurone causes hyper-polarisation of the neurone, the effect is inhibitory. Inhibition and excitation are similar to subtraction and summation with the difference mentioned by Steward (2000) that the former two are performed in a non-linear fashion

The number of inhibitory and excitatory inputs to a neurone increases for neurones closer to the cortex. As the order of neurone rises, a larger area of skin is covered by a single higher order neurone. The number of input neurone synapses with an individual neurone may exceed hundreds of thousands at the cortex level. At cortical areas the connections seem to be complex but in fact are well ordered. During their ascent, nerves from each type of receptor stay closely together, continuing through the thalamus and on to the cortex, creating a topographical map (somatotopic organisation) which repeats itself in any cross sectional cut on the path from spinal to cortex. These maps are normally represented by a caricature termed a homunculus (Latin for "little man"). At the cortical level, the amount of brain devoted to each group of nerves is proportional to the density of the receptors and not to the size of the skin they represent.

Projections from the cortex descend to second order neurones in the spinal cord. These projections, mostly inhibitory, control the flow of the ascending signal by "gating" these signals. The descending feedback is believed to play an important role in "selective perception and attention" (Steward, 2000).

From a physical point of view, changes in temperature affect the system at least three different ways: first, the viscosity and the creep rate of the tissue (see Currier and Nelson, 1992); second, the blood circulation in the tissue; and finally, the conductivity of axons.

Differences between receptor paths

The nerve path from sensor to spinal cord described up to this point is common to all tactile receptors. Tactile receptors can be classified into two groups according to the transmission velocity (depending on the degree of myelination and diameter) of the first order neurones and the path of the second and higher order neurones. Thus, these will be referred to as "slow path receptors" and "fast path receptors".

A fast path receptor transmits signals through myelinated first order neurones (group II or A-β) with a conduction velocity of 25-70m/s (Steward, 2000; Guyton, 1996). Signals then travel through the spinal cord and towards the cortex along the fast path known as the DC-ML (Dorsal Column-Medial Lemniscal). All tactile receptors belong to this group except the free nerve endings. Nerves from the same type of receptor are grouped closer together on this path.

A slow path receptor transmits signals from the free nerve ending tactile receptors. There appears to be some controversy about the role of the slow path receptors in tactile perception. Although the free nerve endings are known to be responsible for detection of touch and pressure (Guyton, 1996), others believe this path contains axons from receptors specialised for pain and temperature (Steward, 2000). First order neurones of slow path receptors are composed of thinly myelinated nerves with an average diameter of 4 μm (group III or A-delta) and a conduction velocity of 10- 30m/s, that is, less than half the velocity of the fast path receptors (Steward, 2000; Guyton, 1996). Nerves of this group pass through the spinal cord along a path known as ALQ (spinothalamic pathway). Signals passing through this path can not be localised on the skin without their interconnection with DC-ML (Steward, 2000).

Note that nerves from different receptor types travelling along these two general paths merge and diverge at different points and in different numbers. Merging of nerves normally occurs at the beginning of the path (peripheral nerve side) and diverging at the central side. For instance, a group of Meissner's corpuscles are supplied by one nerve (Carlson, 1998; Kandel, 1991) or interconnected by nerves running among them (Kandel, 1991; Matzke *et al.*, 1983). Whereas a Pacinian corpuscle is always supplied by a single nerve (Carlson, 1998). This pattern of connection appears to be another example of feature extraction, separating location information from information such as intensity.

3.3.2. Function of the path

The vibrotactile signals are filtered and grouped upon arrival at the skin by three different means; by the properties of the skin and the depth in which each receptors resides; by the rate of adaptation (response dynamic) of each receptor, and finally by the sensitivity of each receptor. These systems work to extract features from the applied signal (feature extraction) and work together in a "parallel processing" fashion.

The response dynamic reflects the way each type of receptor responds to mechanical stimulation over time and is closely related to a phenomenon known as temporal summation. In terms of response dynamic, tactile receptors are classified as slowly adapting, rapidly adapting, and very rapidly adapting (Steward, 2000; Kandel *et al.*, 1991). Conventionally, slow adapting receptors are considered to be those that respond to mechanical stimuli throughout the time that the stimuli are maintained and convey information about the intensity of stimulus. Rapidly adapting receptors respond to the onset and offset of the stimuli. Finally the very rapidly adapting receptors respond only at the beginning of the stimulus and where the dynamic phase of the stimulus ceases (Steward, 2000). In mechanical terms, differences in adaptation rate of the various receptors extract different information from the applied stimulus depending on its load, velocity and acceleration (see Figure 3.11). Note that this is different with some earlier findings reporting that very rapidly adapting receptors (Pacinian corpuscle) are velocity-sensitive (Verrillo and Gescheider, 1975). The faster a receptor adapts to mechanical stimuli, the more extended is its frequency response.

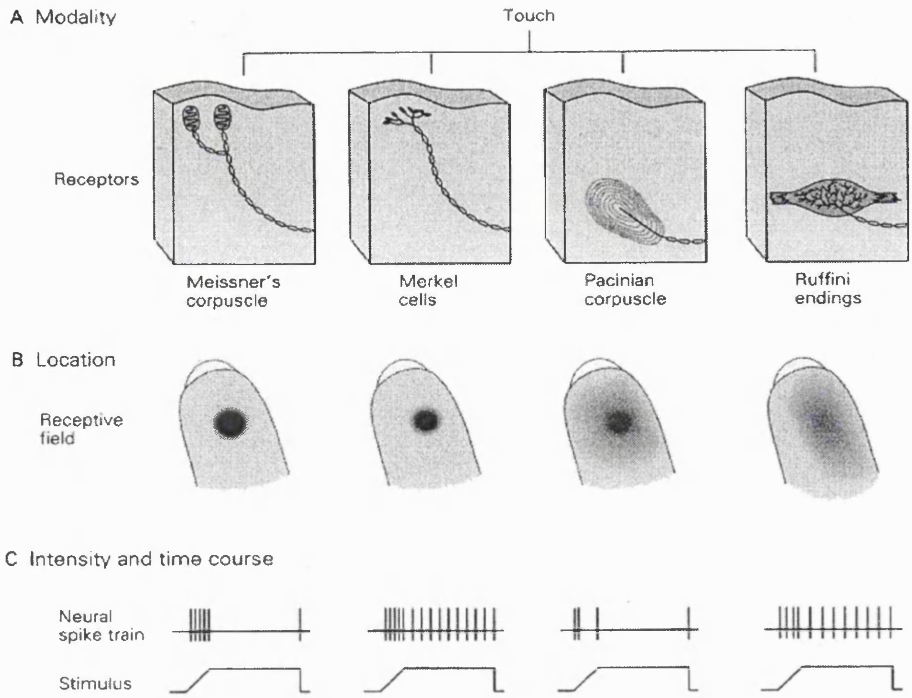


Fig 3.11: Representation of the four main tactile receptors (A), their corresponding receptive area (B) and their neural firing pattern in respond to mechanical stimulus (from Kandel *et al.*, 2000).

Intensity related information is extracted from the signal by differences in the sensitivity of receptors. Conventionally, receptors are categorised as low threshold (very sensitive) to high threshold (sensitive only to strong stimuli). Note that changes in temperature affect receptors unequally.

As mentioned earlier, the signals from the receptors will enter the first order neurones where the parallel processing continues through regrouping. From the functional point of view, regrouping causes an increase in the size of the receptive field (and a larger overlap between receptive fields).

Upon the arrival of nerve signals to the spinal cord, vibrotactile signals begin to be processed in hierarchical fashion while the parallel processing continues. The parallel processing is shown by different pathways within the spinal cord carrying signals from different types of receptor (*i.e.* tactile submodalities) which are grouped together along the ascending path. The hierarchical processing of the tactile sense is reflected in the increase in receptive field of each neurone as the order of neurone increases, and by the existence of the important feature of centre and surround among these neurones. This effect is caused by inhibitory and excitatory connections between the nerves. These connections cause excitation of nerve when the stimulus applied to the centre of a receptive field and inhibition when the stimulus is applied to the edge of the field (see Steward, 2000). This centre and surround effect starts from the level of arrival of stimuli to the spinal cord and is maintained at each relay point up to and including cortex (Figure 3.12). The centre and surround effect is another example of feature extraction in the human vibrotactile system that enhances discrimination between adjacent areas of skin. This pattern of interaction appears to be closely related to summation and inhibition effects explained in Section 3.2.

Nerves from ALQ and DC-ML ascend in different pathways and stay separate up to the Pontine level when they become very close to each other.

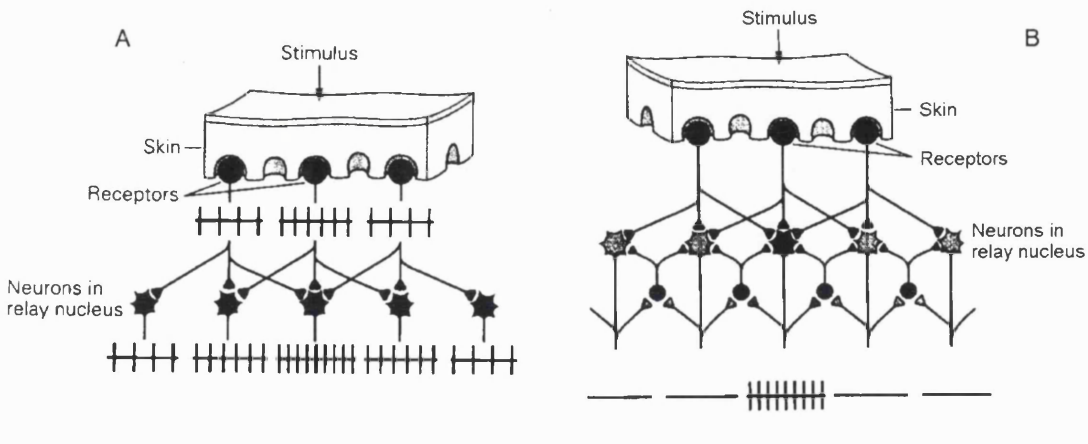


Fig 3.12: Hierarchical processing within the sensory systems. The receptive area of a single receptor increases by connections with other receptors (Fig. A), those closer to the stimulus, firing more vigorously. Addition of Inhibitory and excitatory connections (small interconnecting nerves – Fig. B) narrows the receptive field of receptors by driving the discharge rate of their neighbouring neurones below the resting state (from Kandel *et al.*, 2000).

All these neurones eventually terminate in the thalamus where third order neurones carry this information to the primary somatic sensory cortex (Kandel *et al.*, 1991).

At the cortical level, different subdivisions are dominated by inputs from different classes of receptors. An important function of the processing in the cortex is that the allocated area for each receptor can be modified according to the level of activity of inputs. The segregation of data started at the receptor level is maintained at this level.

The descending neurones from cortex to the lower order neurones controls the flow of the ascending signals by "gating". Gating is another example of contrast enhancement (a phenomenon similar to centre and surround enhancement).

3.3.3 Summary of the physical view of the path

The segregation of information regarding the tactile stimuli starts prior to the tactile receptors, due to the mechanical properties of the skin and the location of the receptors. This segregation continues at the receptor level due to the frequency selectivity and intensity sensitivity of receptors and further at nerve level by differences between nerves in their transmission velocity and their sensitivity.

Within the ascending path, nerves from the same types of receptor stay close together. They interconnect through inhibitory and excitatory neurones. These connections are another important part of neural processing.

Temperature has an effect on the mechanical properties of skin and neural activity of the tactile system.

3.4 Conclusion

Evidence from studies in which the shape and place of applied stimulus to skin are varied and evidence describing the physical properties and connections of the components on the neural path, suggest reasons for the rather varied reports regarding the level of benefit from multi-channel devices.

Section 3.2 established that signals from either single or multichannel vibratory sites interact with each other temporally and spatio-temporally. The interactions range from suppression to enhancement. In the multichannel case the timing of the stimulus and the relative locations of stimulators are two of the determinant factors. Devices employed in studies comparing the performance of single and multichannel devices vary in the configuration of their stimulation site and test materials. Inconsistency in these two parameters during various assessments may have contributed to the observed variation in reported performance. This explanation is in agreement with suggestions of Eberhardt and Bernstein (1990). Furthermore temperature is a factor that unequally affects perception through the various tactile channels (see Bolanowski, 1988). Since different aspects of mechanical stimuli such as velocity and acceleration are segregated through different vibratory channels, it appears logical to conclude that the perceived pattern of stimuli involving more than one channel will be affected by changes in temperature.

Section 3.3 established that the integration of a vibratory stimulus does not solely occur in cortical areas but starts from almost the point where the stimulus is applied. In fact, the interactions noted during psychophysical reviews (Section 3.2) are part of this integration process and essential for the tactile sense to perform. Furthermore, the physiological study suggests that ascending nerves from each type of receptor stay closely together. This close grouping perhaps can explain results of studies which suggest integration of information from distant body loci may be more difficult than single or closely located points (for example see Eberhardt and Bernstein, 1990).

The closing remark of this chapter is that a tactile receptor known as the Pacinian receptor appears to have rather special position in the vibrotactile communication (see Chapter 2). This is not surprising as these receptors offer a wide frequency response and are also supplied by a single nerve. However, when these receptors are to be targeted for use by a stimulator other properties of them should be taken into consideration. They are fast adapting receptors sensitive to changes in acceleration (Figure 3.11) which demands the use of suitable mechanical stimuli. They reside deeply within the skin and hence have larger receptive areas compared to some other tactile receptors and are more sensitive to changes in temperature.

CHAPTER 4

MOTIVATION FOR STUDY

4.1 Introduction

This chapter presents the hypothesis, brings forward evidences in its support and outlines the approach taken to test the hypothesis.

4.2 Hypothesis

The hypothesis presented here is based on two assumptions. The first assumption is multichannel devices provide a wider communication bandwidth compared to a single channel device. The second is that the patterns created at spatially close points on the skin are more readily linked and processed than those placed some distance apart (see Section 3.4). This work is an attempt to evaluate the degree of interaction between waves travelling within the skin in various propagation modes. It is expected to contribute to develop a multichannel vibratory system with less interaction between its vibrators. This study aims to test a main hypothesis as follows:

"Reduction of mechanical interaction between vibratory signals results in improved performance of multichannel devices."

Providing that the hypothesis is true, removing interaction would be expected to lead to a clearer correspondence between the vibration pattern presented and that perceived, leading to a spatial representation of the pattern that is less dependent on the intensity and frequency of each vibrating point. If this is the case, a more restricted spatial pattern per vibrator is expected to facilitate learning to use vibratory information.

In addition, reducing interaction will allow the possibility of reducing the distance between the vibrators. This may result in the reduction of the overall size of the device, a factor considered important towards the portability and applicability of the device (see for example Cholewiak and Wollowitz, 1992).

Furthermore, assuming that the synchronisation of the delay between the vibratory stimuli and their representation in the central nervous system is an important parameter in the final perception of the simultaneous signals (see Section 3.4), closer vibrators may result in a more synchronised representation of vibrotactile signals

4.3 Supporting evidence for the hypothesis

Before discussing ways of reducing interaction, it is reasonable to ask whether the interaction exists. There are four reasons to believe that the interaction does exist.

First, there is physics involved in vibrotactile stimulation. Waves of any nature travelling in the same plane of movement can interact with one another and waves travelling in a viscoelastic tissue are no exception. However, the situation may be rather different if the waves are damped by the medium in which they travel. In other words, they may not travel far enough for interaction to take place. On the basis of existing knowledge it is difficult to estimate whether the latter is what happens to waves travelling in different directions generated by a vibrotactile device. However, there are reports suggesting that at least these waves can travel long distances on the surface of the skin (Békésy, 1955; Gescheider *et al.*, 1978; see also Cholewiak and Wollowitz, 1992) and precautions such as a rigid surround were introduced to reduce them. The lack of information about the behaviour and the distances that intra-tissue wave can travel *per se.* stresses further the necessity for the experiments that will be reported.

Second is the reported improvement in performance in experiments using multi-vibrators in which each of the simultaneous vibrations is applied in a different plane compared to devices using a single plane of vibration (*e.g.* Spens *et al.,* 1998). This improvement may be due to reduced interaction between the vibrators.

Third, there are reports comparing the performance of single and multi channel devices (see Section 2.3). The fact that years of development of advanced signal processing methods and application of different encoding strategies has not yet resulted in significant performance difference between multichannel and single-channel devices demands an explanation. Excessive interaction may be one way of accounting for this failure.

Finally, there is evidence from the pilot studies for this work. Using conventional perpendicular vibrators, it appears that waves generated by two vibrating points with a slight difference in their frequency can interact with each other resulting in the perception of a non-existing wave with a frequency and amplitude different from both original waves (beats). Occurrence of a similar situation during the use of a multichannel device may degrade or alter the perception of the intended signal in a rather unpredictable fashion.

4.4 Experiment

Mechanical interaction between vibrators can be reduced on the basis of propagation of waves. Waves in general can propagate in the mass of a solid by two means; longitudinal and transverse. Waves travelling in one plane can not interfere with those travelling in a different plane. On this basis, there are two alternatives to reduce mechanical interaction. The first is to place vibrators so that their axis of movement are perpendicular to each other. The disadvantage for this approach is that stimulation site would be limited to body sited with orthogonal planes (*i.e.* finger tips).

The second alternative is to create a situation with the same plane of stimulation but a different plane in which the displacement takes place. An obvious advantage of this alternative is that the stimulation site is not limited to areas with different orthogonal planes. Note that in both of these alternatives, interaction may occur due to the Poisson's ratio of the tissue, by causing waves to propagate in planes different to that of the original.

Figure 4.1 illustrates the concept of the second alternative, by showing three basic modes of displacement. The first mode, *transversal oscillation*, is when the displacement of the object is tangential to the surface of the skin. The second mode is known as *longitudinal oscillation* which refers to the displacement perpendicular to the surface of skin. The last mode shown is called *rotary oscillation* when the oscillation applied to the skin is torsional.

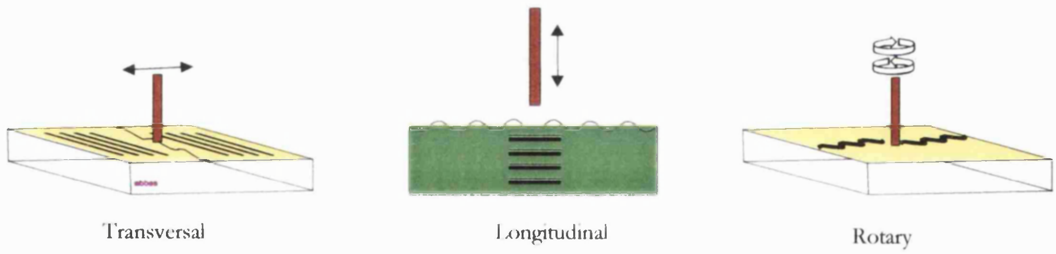


Fig 4.1: Waves generated by different displacement modes, travelling in different planes in a medium.

Despite the logic of the above solutions in reducing interaction, performing them poses major difficulties. The review of previous works suggests that even if the required prosthesis was already available, the evaluation of such a prosthesis on subjects will require time in excess of this project.

A different approach has been taken to investigate the effect of the plane in which the wave propagates on perception and subsequent interaction. This approach uses a behavioural measure to estimate the degree of the interaction between waves.

The main concept of the method to evaluate the level of interaction (a non-invasive, in vivo experiment) is based on the detection of beats. Two waves, slightly different in frequency are presented simultaneously to the subject's index finger and report of whether beats have been detected is demanded. Detection of beats is taken as a measure of the interaction. The more detectable are the beats, the greater the inferred degree of interaction.

Now that the logic of the approach to measure the interaction has been introduced, this project focuses further and defines its objectives as assessing whether the introduced method of measuring interaction (*i.e.* detection of beats) is practical and if so, whether the concept of using different planes of vibration is an efficient way to reduce the interaction.

To achieve these objectives, in the forthcoming experiments the degree of interaction between a pair of torsional (rotary) vibrators and that between a pair of perpendicular vibrators will be evaluated.

During this preliminary test, only some of the variables affecting the threshold will be controlled. This is aimed at reducing both the required time and cost of the assessment, at the price of introducing a level of error into the results. This is essential prior to the design and preparation of an extensive and detailed evaluation (if required).

4.5 Conclusion

This chapter has discussed the hypothesis, namely the possible mechanical interaction between vibrators of multichannel vibrotactile displays, evidence supporting it and approaches for testing it. Details of the devices built and the psychophysical tests developed on the basis of the hypothesis will be explained in the following two chapters.

CHAPTER 5

DESIGN AND CONSTRUCTION

5.1 Introduction

This chapter describes the construction of the perpendicular and rotary tactile stimulators, a photometric measuring device and the connection of these devices to other equipment used in this study.

5.2 Perpendicular vibrator

A perpendicular vibrator refers to a vibrator whose axis of movement is at right angles to the surface of skin. The design of the perpendicular vibrator is based on a piezo ceramic material. Piezo ceramics are transducers which change their physical dimensions in response to an applied voltage (reverse piezoelectric effect).

5.2.1 Why piezo design?

Electromagnetic based actuators are often used in vibrotactile experiments. They offer a wide frequency band and are able to deliver sufficient mechanical power suitable for stimulation of all tactile receptors (see Cholewiak and Wollowitz, 1992). However, they are bulky in size and their smaller versions do not offer similar performances (for example see Fukuda *et al.*, 1998). Since this study required the two stimuli to be applied in close proximity of each other, some modifications to the commercially available actuators were required. Hence, it was decided to build a pair of perpendicular vibrators.

Piezo actuators offer some advantages over electromagnetic devices. They present no wear and tear, as the displacement in piezo ceramics is based on solid state dynamics. They are extremely energy efficient as they only absorb energy during movement. Static operation, even supporting heavy loads, does not consume energy.

There are also some disadvantages associated with piezo designs. They require a high driving voltage (on the order of 100 volts) which in turn mandates consideration of safety requirements in the design. The maximum displacement generated by them is very small (on the order of a few tens of micrometers). This small movement is not sufficient to stimulate all tactile receptors across the relevant frequency range. In addition, the piezo ceramics have a brittle crystalline structure. They can withstand considerable compression load but very little tensile or shear force. They are also prone to damage by the resulting dynamic forces caused by running them under their maximum displacement (stroke and load) at their resonant frequency (the resonant frequency of an actuator varies with applied load as the square root of the mass). Finally piezo ceramics can age and lose their gain.

5.2.2 Design

The design implemented here aimed to overcome the disadvantages attributed to piezo ceramics while providing displacements in excess of 30μm across the 20-500Hz frequency range (the desired displacement value estimated from the work of other researchers- for example see Lamoré, 1988).

Figure 5.1 illustrates the design. Each cell of the actuator is composed of two piezo benders mounted together by means of pivots (A1) and (A2) so as to create space (S) between the inner surfaces of benders while at rest. Bars (R1) and (R2) provide the main axis, in which the displacement occurs, providing the finger's resting point at one end while at the other end fixed on a rigid mass of approximately 0.420kg. The two benders are electrically connected in parallel so that their respective displacement are in opposite directions relative to an axis passing perpendicular to their supporting layer.

This design addresses the described disadvantages associated with piezo ceramics for vibrotactile applications as follows.

- High voltage: in general, the potential danger from electric shock is due to the current flow and its pathway rather than the voltage itself. The current required by the device is proportional to the area of its contact with the skin. To assure the safety of the device for cases that the current to the actuator exceeds 10mA at 100Hz (safe let-go current level) the encapsulating surround formed by supporting layers of the two benders was earthed. Safety was further improved by electrical isolation of the finger resting point from the vibrating axis by polyethylene materials (Figure 5.1, number 3). The device complies with class A (earthed) and BS 5724 (the UK version of IEC 601) regulations
- Small displacement of piezo actuators: in the adapted configuration the generated displacement by piezo ceramics is improved by a factor dependant on the length of each piezo crystal and the length of the

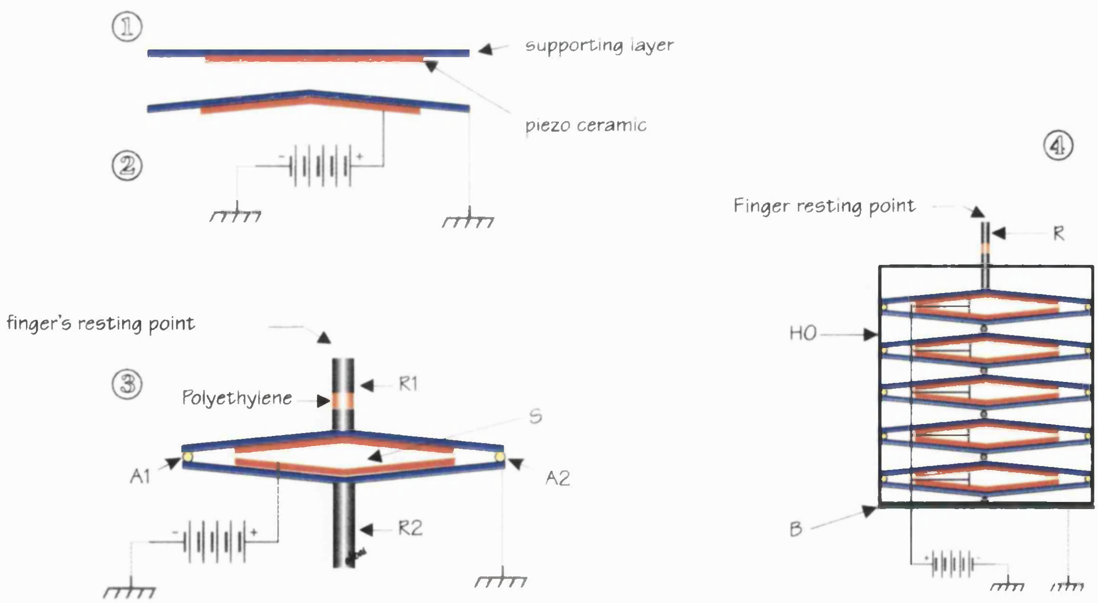


Fig 5.1: Design concept for the perpendicular vibrator. Piezo-electric benders. (1) Relaxed (2) Activated (3) Assembly of a perpendicular vibrator and (4) stacked configuration to improve the displacement (not to scale).

supporting layer. The piezo-benders implemented in this study have a circular ceramic area with a diameter of 25.0mm and a supporting layer made of brass with a diameter of 35.0mm. However if further increase in displacement is required it is possible to stack cells on each other (Figure 5.1, number 4). The resulting displacement in this case is simply the sum of the displacement generated by each cell.

- Brittle structure of piezo ceramic: in the intended application there are three possible unwanted forces on the axis (R) and hence on the ceramic, including torsional and bending moments and compression forces. In the normal condition there will be no application of tensile force. The supporting layer of each bender provides a degree of protection against the first two forces. However for cases in which the axis (R) is long or its cross-section is small the crystal can be further protected from bending moment of the axis (A) by the protective housing (HO). This housing provides the mean to eliminate the effect of bending moment on the piezo ceramics by holding the rod (R) perpendicular to the base (B).
  Protection against the compression force on axis (R) and subsequent tensile/compression force on the ceramics is provided by the limited gap (S). The gap closes when the safe level of the load is exceeded, allowing any compression force applied to axis (R1) and hence to the upper ceramic to be transferred to the lower ceramic and subsequently to the lower axis (R2).

- Ageing of the ceramic: ageing is not considered to be a major design problem, as it can be overcome by applying a higher voltage in the poling direction compared to the voltage applied in the inverse to poling direction. The poling direction is a specific plane in the piezo ceramic, specified in the manufacturing process in which the highest expansion of the ceramic occurs while driven by the highest voltage.

5.2.3 Assembly

During the assembly the following points were considered.

- The critical (Curie) temperature for the most widely used piezo ceramic, Lead Zirconate Titanate also known as PZT (Pb (Ti, Zr) O3) is around 200°C. Exceeding this temperature during construction or operation can cause irreversible changes in the crystalline structure of the materials with a possible loss of piezoelectric properties.
- A change in crystalline structure can also happen by exceeding the mechanical and electrical limits of the material.

For the purpose of this study a pair of the described vibrators without a protective housing was built and mounted in a frame 10mm apart as illustrated in Figure 5.2 An aluminium extension (dimensions 0.5×6×5mm) mounted on the vibrating axis provides an area where the displacement of the vibrator can be measured. This extension will act as a "beam interrupter" described in the design of the photometric device (PMD) under Section 5.3.

The finger resting points with the inner diameter of 3.2mm and outer diameter of 4.7mm were chosen to comply with the design of the rotary vibrator for the intended comparative study. The design of the rotary vibrator is described in Section 5.3 and the framework for the comparative study is explained in Chapter 4.

For the purpose of the driving circuit, the perpendicular actuators were considered as a capacitive load. This implies that the expansion of the ceramic is considered an exponential and predictable function of the applied voltage. In a real situation the value of this capacitance can change up to 200% depending upon amplitude, temperature and load (Piezo systems). To

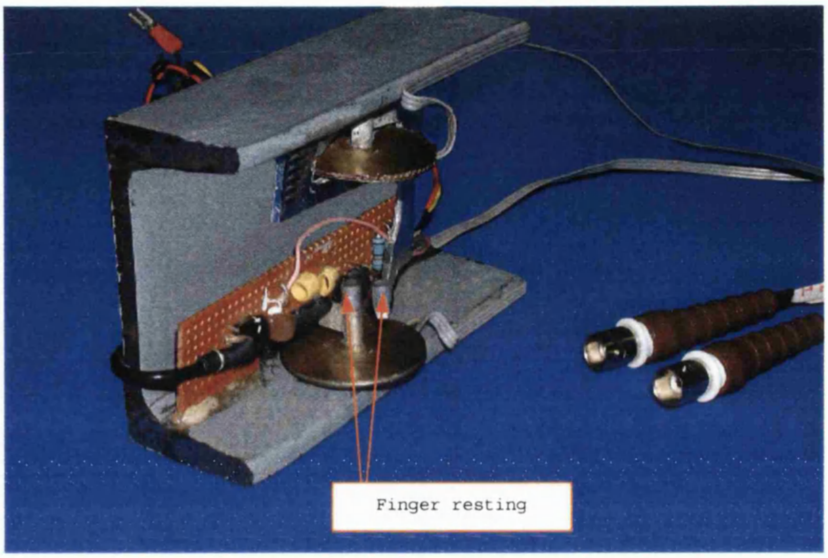


Fig 5.2: Showing a pair of the perpendicular actuators used during this study. The mounted photometric device (PMD) is described under Section 5.3

correct errors arising from this assumption, processes were devised which will be explained in Chapter 6.

Although this design has been developed and constructed for the needs of this project, later it was found that aspects of the design were similar to a commercially available actuator.

5.2.4 Technical specifications of the perpendicular vibrator

A summary of mechanical and electrical characteristics of the perpendicular vibrator is presented in Table 5.1.

Table 5.1: Specification of the perpendicular vibrator

Electrical	Maximum input voltage	63	V_{pp}
	Resistance	>2	MΩ
	Capacitance - unloaded	52.6±1.35	nF
Mechanical	Corrected frequency range	20-500	Hz
	Contact area	9.3±1.2	mm^2
	Mass	0.420±0.005	kg

5.3 Rotary vibrator

The term "rotary vibrator" refers to a vibrator that applies an oscillating torque to the surface of the skin. This is unlike the conventional vibrators in which the force is applied either perpendicular or transversal to skin. There appears to be no use of rotary vibrators in tactile communication prior to this study. The required force for displacement of skin can be estimated from the previous reported Modulus of elasticity (for example see Sanders, 1975). The unavailability of information regarding the required force and the sensation which arises from torsional vibration made the priorities and approach to this design different from that of the perpendicular vibrator explained earlier. The following section describes the structure of the rotary vibrators made for this study.

5.3.1 Why an electromagnetic design?

An electromagnetic movement was used to generate torsional oscillations in the rotary vibrator described here.

Despite the numerous advantages associated with the use of piezo-ceramics (described in Section 5.2), electromagnetic designs (based on a voice coil) offer some advantages in generating the torsional oscillation. High angular displacement is more easily achieved by a design based on magnetic force than the one using piezo-ceramics. The availability of off-the-shelf designs eliminates the need for custom manufacture of the electromagnetic prototype, reducing the development cost and time. These devices are low voltage actuators, which in turn eliminates the safety concerns that would have arisen from the use of the high voltages necessary for piezo ceramics. In addition the advantage of piezo actuators to "bear static load without the use of energy", justifying their use in the perpendicular design, is not considered to be relevant for generating torsional oscillations.

There are also some foreseen disadvantages in the use of magnetic force. In such a design as the frequency increases and hence higher force required to overcome the affect of inertia (higher acceleration hence higher force), the inductive reactance of the coil ($X_l = 2\pi fL$, where L is inductance) increases. This doubly negative effect at higher frequencies is expected to greatly reduce the maximum displacement as the frequency increased.

Another disadvantage of using electromagnetic design that particularly applies to this study would be the need for a driving system capable of handling a very wide dynamic range in voltage, controllable within 1-2dB. Since the capacitance reactance (perpendicular vibrator) will be affected in a different way to the inductive reactance (rotary vibrator) by frequency *i.e.* $1/C\omega$, $L\omega$. The required voltage to amend this is in addition to the 50dB tactile dynamic range (see Section 3.1), ≈30dB change of tactile threshold in the frequency range of 20-500Hz, the absolute threshold difference between subjects and the unknown shape of the tactile threshold for the rotary vibration. These variations resulted in an estimate of the required range of driving voltage in excess of 100dB.

5.3.2 Design

During the design and construction, priorities were (in order of importance), reduction of the mass of the vibrating shaft, prevention of vibration from being transmitted to other body sites (physical isolation), cost, power consumption, and finally the size of the device.

- Vibrating mass: the mass of the vibrating shaft affects its maximum displacement particularly at higher frequencies due to its inertia. The excess input energy required to produce the higher acceleration will appear partly as heat, which may reduce the efficiency of the system further by increasing the resistance of the coil, or it may cause permanent damage if the melting point of the isolator being used is exceeded. Care has been taken to reduce the mass of the vibrating assembly (VA) and to dissipate the generated heat (Figure 5.3). The mass of the VA was reduced by selecting a light material (aluminium and plastic) and by adopting the fixed magnet and movable coil configuration. Likewise, the current to the coil was limited by the use of a fuse to prevent the possibility of heat damage due to excessive current.

- Force and angular displacement: since the radius of the finger resting point might need to be changed during experiment, the generated force by the coil/magnet assembly and their mounting distance from the main shaft needed to fulfil two requirements: 1) to provide enough torque for the largest finger resting point 2) to provide enough angular displacement for the smallest finger resting point.

- Physical stability of the system: In the perpendicular design, the problems of propagation of vibrations through the equipment and possibility of wave degradation (damping) through any reaction forces was resolved by simply mounting the vibrator(s) on a heavy metal mass. In the rotary case, there is no need for a heavy mass. The reaction generated by a torsional force, which is also torsional, can be withheld providing there is enough friction between the vibrator and its supporting surface. To improve gripping in the most stress concentrated points (*i.e.* the finger resting point), which are the points more prone to slipping, the shape of the contact point was modified so that the highest stresses would be concentrated on the circumference. This was achieved by lowering the centre of the circular contact point. A centre hole provides two further advantages: 1) a reduction in the load on the vibrator, and; 2) enhanced contact between the vibrator and the uneven structure of the finger. These factors result in an improved displacement range of the vibrator and a more accurate estimate of the contact area respectively.

- Phase/frequency: Inductance changes the phase of a signal as a function of frequency. For the purpose of this study no special treatment of phase is required so long as only comparison between similar types of vibrator are made.

The rotary vibrator was based on a modified SEAGATE hard disk (model ST942AG). Figure 5.3 provides an illustration of the way the rotary vibrations were generated. The vibrator consists of the main shaft (VS) made of steel, which can rotate along its long axis. The shaft was connected at the one end to a plastic rod of 4.7mm diameter providing a finger resting point and the other end to a perpendicular supporting frame by means of a ball bearing. An aluminium extension mounted perpendicular to the main shaft (VS) provides the support for the coil (L) which can move between the poles of the two magnets S and N shaped as a sector of an annulus. The coil (L) is composed of 4.7m of laminated copper wire with the diameter of 0.1mm wound around a light, 1mm thick plastic shape matched to the magnets *i.e.* the sections of annulus had the same radius as the magnets but a smaller width (Figure 5.4). The particular shape of the magnet and the coil allows maximum displacement with reduced overall size. A miniature 0.2A fuse mounted on

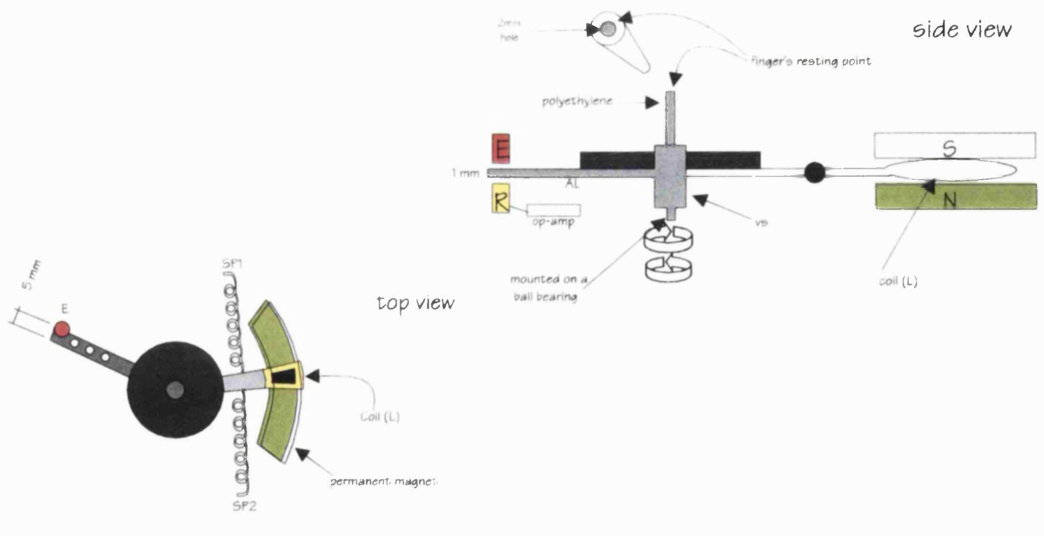


Fig 5.3: Design concept for the rotary vibrator. Diagram showing the different parts. "Vibrating assembly" refers to the collection of vibration shaft (VS), coil and aluminium extension (not to scale).

the vibrator protects the coil against excessive currents.

The coil is kept in the centre of magnets by means of two springs SP1 and SP2 in the inactivated state, assuring the coil always starts its motion from this point and is displaced equally clockwise and anticlockwise by equal plus and minus input voltages. The force applied by the springs at any particular distance (Δx) from the centre point varies according to the "spring constant (κ)", by equation $f=\kappa\Delta x$. This variation is kept at a minimum by selection of a relatively long spring with small κ. The contact or the "finger resting point" has a circular cross section with the diameter of 4.7mm with a hole of diameter 3.2mm in the centre. This provides a contact point in the shape of an annulus with the area of approximately $0.09cm^2$.

The space between the magnet assembly and the main shaft (VS) is reserved for use by a photometric device (PM) described in Section 5.4. This is assuming that the electromagnetic fields in the vicinity do not disturb its function. Otherwise, the PMD could be mounted opposite the magnets by adding the extension AL. In practice, this second alternative was used.

Figures 5.4 and 5.5 show the completed main shaft and prototype assembly. The prototype is comprised of two vibrators mounted together by means of a screw (SC). The screw provides a centre around which the vibrators can rotate and subsequently the distance between the two vibrating points can be adjusted for different experiments.

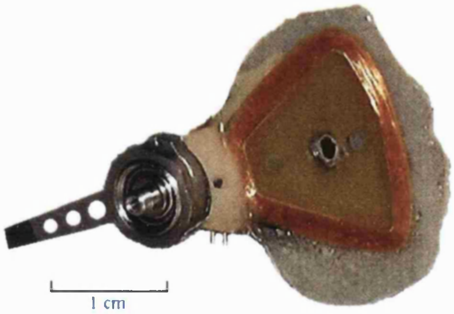


Fig 5.4: The lower view of the vibrating assembly. The excess moulding around the coil will be trimmed in the stages to follow.

5.3.3 Technical specifications of the rotary prototype

A summary of mechanical and electrical characteristics of the rotary vibrator is presented in Table 5.2.

Table 5.2: Specification of the rotary vibrator

Electrical	Maximum input voltage	11.1±0.1	V
	Resistance	13.9±1	Ω
	Impedance unloaded	0.65	mH
Mechanical	Corrected frequency response	20-500	Hz
	Maximum torque	$(1.20 \pm 0.02) \times 10^{-2}$	Nm
	Rotating angle	±10.5°	degrees
	Contact area	9.3±1.2	mm^2

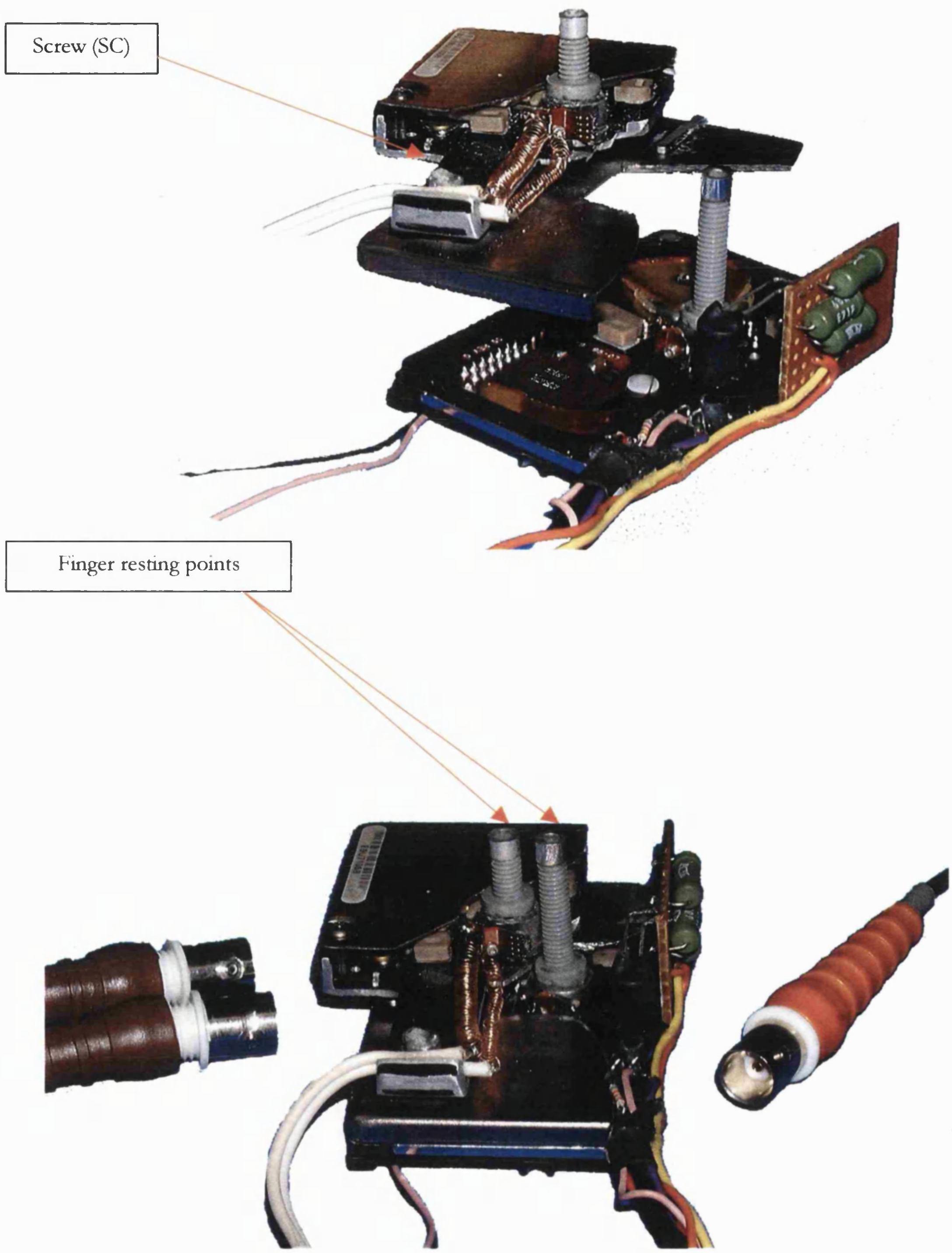


Fig 5.5: Assembly of the rotary vibrator. The completed prototype (the lower photo) and illustration of the mounting position of two vibrators with respect to each other (the upper photo).

5.4 Photometric device (PMD)

The term "photometric device" refers to an optical device consisting of a light source and a light detector. The device in its ideal form alters its output current keeping it proportional to the displacement of any object in its light path. A pair of PMDs was built and incorporated into both the perpendicular and rotary vibrators. Following calibration (see Section 5.4.4), the PMDs can serve two main functions: 1) measuring the frequency response of the system and, 2) measuring the actual displacement under psychophysical test conditions.

5.4.1 Advantages and disadvantages

Optical devices offer some advantages over alternative displacement measuring methods. They add no extra mass or resistance to the oscillating object and hence they will not affect the system's frequency response. They also offer a wide frequency response and are low cost.

Foreseen disadvantages associated with the use of PMDs are:

- The possibility of contamination of the output signal by ambient light, electromagnetic sources or mechanical oscillation of the PMD.
- The difficulty in obtaining a light source giving truly uniform illumination, essential for assuring that any voltage read-out from the PMD is a true representation of the actual displacement of the vibrator.

5.4.2 Design

The following points were considered during the design and subsequent production, aimed towards countering the possible disadvantages of using a PMD.

Mechanical stability: The main causes of mechanical instability are the movable parts of the PMD. This problem was reduced by mounting the PMD on the same reference frame as the vibrator and selecting the shortest possible connections between components and the PCB. When there were unavoidable cases where mechanical stability could not be guaranteed (*e.g.* the "light pipes" between the light source and detectors) as an alternative a "bridge" was made between the two components, securing each part to the PCB (see Figure 5.2).

Optical stability: The affect of ambient light was reduced by narrowing the angle of view of the light detector to the light emitter and by simultaneous use of a light filter and a source-sensor pair matched to a narrow frequency band. Narrowing of the angle of view was achieved by use of a relatively long pipe (where possible, twice as long as the diameter of the pipe) and use of a narrow angle LED. The only special measure taken to ensure the uniform illumination was to minimise reflections by the use of matt black pipes.

Electrical stability: This was improved by placing the components close to one another and shortening the electrical connections (also improving the bandwidth), by shielding all sections including the PCB and by separating power lines to the op-amp from that of the light source.

Figure 5.6 shows the block diagram of the PMD. A circuit consisting of an op-amp (OPA177) with a closed-loop bandwidth of 0.5 MHz was used in a simple "inverted amplifier" mode known as "photoamperic mode". In this mode, the output (V_{out}) is equal to $V_{out} = -I_p.R_f$ [♣]where the I_p is the photodiode current and R_f is the feedback resistance. The photodiode current is proportional to the radiant power (in watts) falling on the photodiode (PD410). In the present design, the value of R_f was set at 100 KΩ.
The photodiode (detector) and photoemitter were each placed at one end of separate "light pipes" (each of diameter 3mm) with lengths of 10mm and 5mm respectively for the perpendicular vibrator. The pipes were mounted with their open ends facing each other separated by a distance of 4mm. The

[♣] If the cathode of the LED is connected to the negative input of op-amp then $V_{out}=I_p.R_f$

PMD beam interrupter (described in the Sections 5.2 and 5.3) moves in the plane perpendicular to the light beam, creating a voltage at the output of the op-amp proportional to change in light intensity at the detector passing through the pipes.

However, because the cross section of the light pipes is circular, the relation between the displacement and the output voltage across the PMD is not a proportional relation. The relation is even more complicated for the rotary vibrator since the beam cutter cuts the cross section of the PMD in an angular motion. Calculations show that even for the case of the rotary vibrator this relation can be approximated to linear for a large potion of the displacement taken place within the cross section of the PMD (see Appendix 1).

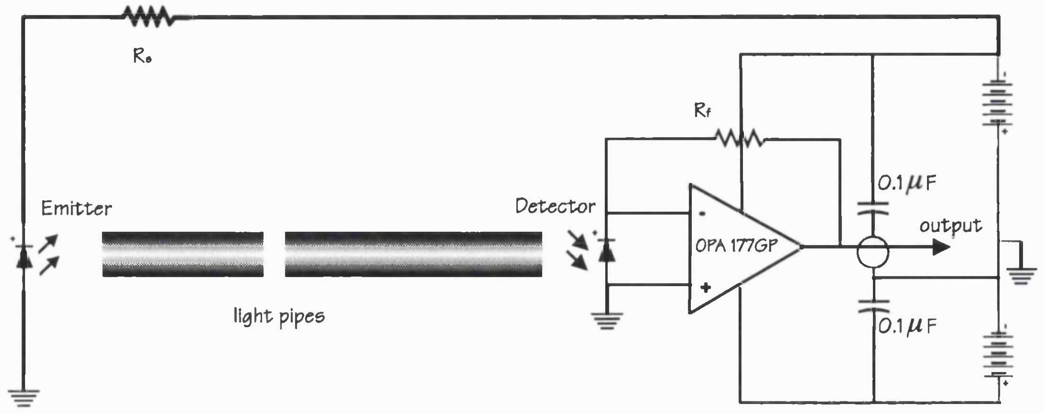


Fig 5.6: Schematic diagram of the photometric device.

5.4.3 Technical specifications of the PMD

A summary of the characteristics of the PMD is shown in Table 5.3.

Table 5.3: Specification of the PMD

Supply	Maximum voltage - (balanced line)	24	V
Response	Frequency range	1-500	Hz
	Maximum displacement for linear response	≈±0.7	mm
	Max output voltage	±8	V
	Sensor area	0.07	cm^2

5.4.4 Empirical calibration of the PMD

The process by which the PMD was calibrated empirically was carried out in addition to the theoretical calculations made during the design of the PMD (Section 5.4.2). The empirical tests verify the calculations and their assumption (*i.e.* uniformity of illumination) by simultaneously measuring the actual displacement of the vibrating shaft at the point on the beam interrupter using a microscope and recording the corresponding voltage changes across the PMD across the frequency range. Since the relation between the displacement of the rotary vibrator and the PMD output is more likely to be non-linear, these tests were carried out using the rotary vibrator. Data from these tests also provide an estimate of the real displacement (in a standard unit of displacement) in relation to the output from the PMD. This is not essential for the purposes of this comparative study. However, it is useful if the results of this study are intended to be compared with the others.

Prior to calibration, the following two tasks were performed for both the rotary and perpendicular vibrators. Firstly, the intensity of the light from the emitter in the PMD was adjusted by means of a resistor in series (R_s), chosen so that with the path between emitter and the detector fully open the voltage across the op-amp dropped to 90% of its saturation value. The PMD frame was subsequently moved so that the PMD beam interrupter on the vibrating shaft covered half the path of the beam causing the output of the op-amp to be half of its value with the light path open. Note that all the electronic components used in the design of the PMD have a frequency range which allow operation at least one octave higher than the maximum frequency at which they were intended to be used.

A LEICA-MZ8 microscope (magnification x50) with a graded ocular and a Philips oscilloscope model PM 3206 were used to measure the displacement of the vibrator and the voltage across the op-amp respectively. Details of the measurements are included in Appendix 2. Plotting the measured displacement against the corresponding output voltages from the PMD (observed at a variety of frequencies) results in a good approximation to a linear relationship (Figure 5.7). On the basis of these data the ratio of displacement to the corresponding output voltage was approximately (11μm/V).

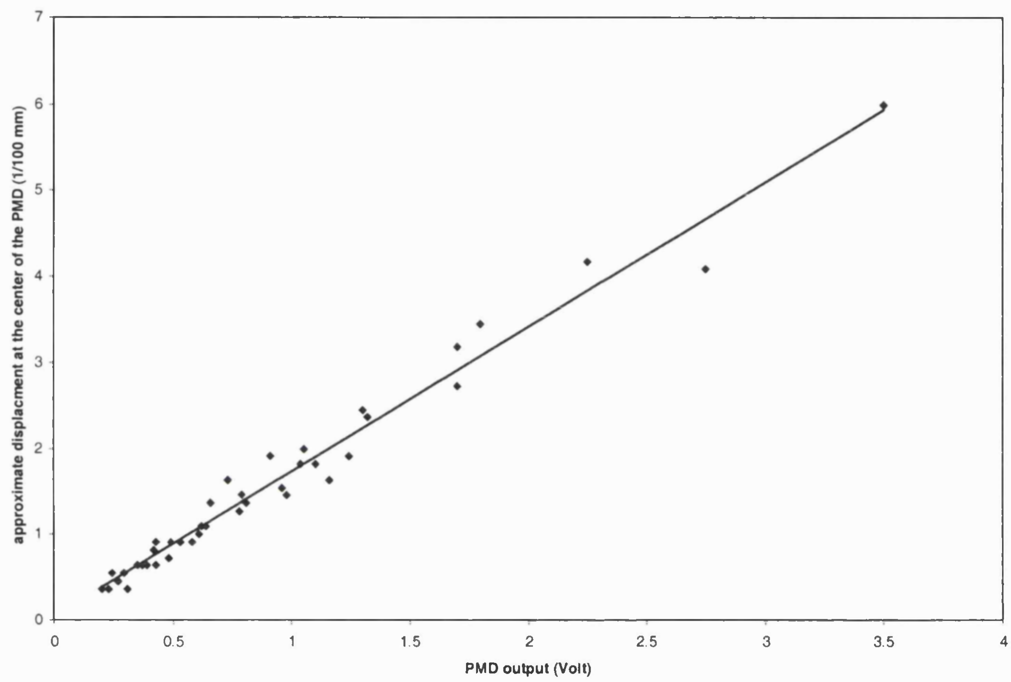


Fig 5.7: Empirical test of the PMD. This shows a linear relationship between the displacement within the light path and the corresponding change in the output voltage from the PMD. The values on the Y-axis are values at the distance of 20.1mm from the centre of the vibrating axis.

Thus, (within the error range) the output voltage of the PMD is a true measure of the displacement. These results are comparable with the calculations carried out during design of PMD described under Section 5.4.2

5.4.5 PMD and the rotary vibrator

The applied mechanical stimuli can be contaminated by both electrical and mechanical noise. To assess the level of each type of noise, the level of harmonics within the applied signal and the PMD and also the cross-talk between the rotary actuator and PMD were estimated.

The level of the harmonics were measured at 0dB SL, with the vibrator being driven by the same signal used for the psychophysical tests (a computer generated sine-wave). The anti-alias filter was removed from the system and the connection cables between the vibrator and the source were extended to twice their normal length. These conditions were chosen to simulate an extreme working condition of the vibrator. Measurements showed that the level of the harmonic components reached their highest value at 250Hz and never exceeded -15.6dB SL.

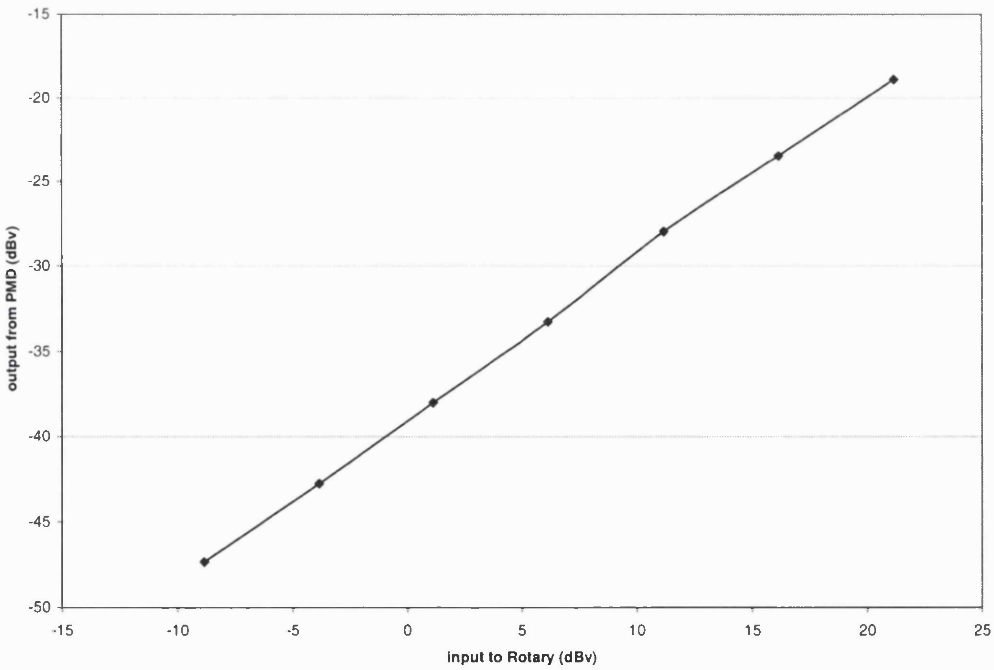


Fig 5.8: Testing the linearity of the PMD where both input and output voltages are expressed in dB. Data collected from the rotary vibrator stimulated with 500Hz digitally generated sine-wave signal. The peak of the input voltage is equivalent to about 50dB SL rotary at 500Hz.

The total level of mechanical and electrical noise was slightly higher than this value, approaching -11.8dB SL at 200Hz. The main source of the noise was components from the electrical mains.

Cross-talk is another cause of contamination of the output from the PMD. The main sources of cross-talk are the electric and magnetic fields around the vibrators. These two sources induce currents in all conductive sections of the neighbouring PMD circuits, resulting in errors when measuring output voltages. The induced current is inversely proportional to the square of the distance between the source and the induced section and is highly dependent on the length and orientation of the section. Precautions were devised and applied to reduce the effect of this error as explained previously. This effect is quantified by measuring the ratio of the input voltage (to the vibrator) to the output voltage across the PMD while the light path was blocked. This value was greater than 55.6dB, having its lowest value at 200Hz (measured at 40dB SL).

In the next series of tests that were carried out at some predetermined frequencies (the choice of these frequencies will be explained in the next chapter), the intensity of the signal was varied whilst the output from the PMD was recorded. There were two very closely related reasons for these tests 1) they provide an estimate of the input-output response of the system (response with respect to changes in intensity) and, 2) providing that they response is linear, they provide further evidence for the linearity of the PMD. Figure 5.8 shows an example of the results obtained at 500Hz. In this figure, the maximum input voltage corresponds to approximately 50dBSL (at 500Hz for the rotary vibrator).

These tests suggest that, over the tested range of intensities both the behaviour of the rotary vibrator and the PMD can be approximated by a linear system.

Following these tests, the frequency response of the rotary vibrator was measured. Figure 5.9 shows the response of the rotary vibrator across the frequency range. The measurements were performed using a spectrum analyser ONO SOKKI-910 (the term "spectrum analyser" will henceforth refer to this device unless otherwise specified). This graph shows that the response is highly dependent on the load on the vibrator particularly at frequencies lower than about 50Hz. Information from the loaded case *i.e.* when the vibrator was in contact with a subject finger, will be used to correct the response of the rotary vibrator in the psychophysical tests.

Figure 5.10 shows data obtained by measurement using the microscope. This graph shows a similar pattern to that of the data from the spectrum analyser (data in the Appendix 1) Note that both sets of information suggest that the system resonance at a frequency around 225-235Hz. This has been taken into consideration during the psychophysical tests and no psychophysical test was performed within this frequency range. The graph in Figure 5.8 is consistent with the power law formula $V_{out} = 1.188 \times 10^{-2} V_{in}^{0.96}$, which approximates the curve across an intensity range of more than 30dB. The values of the power and scale factor were obtained from the graph and, allowing for experimental error, it is possible that the true value of the power is actually 1.0, which would indicate that the output voltage was directly proportional to the input voltage.

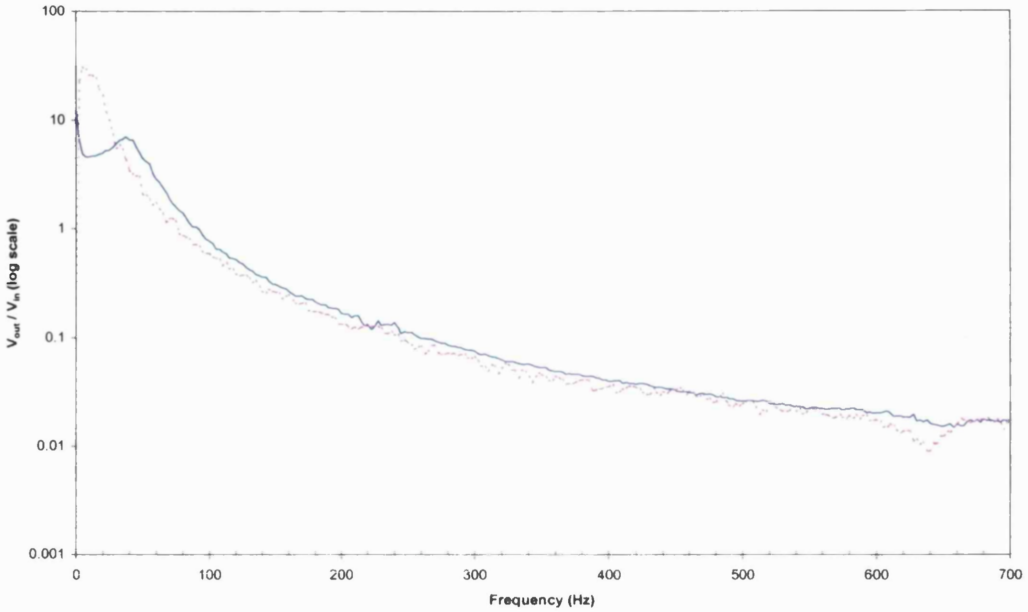


Fig 5.9: Graph showing the frequency response of the rotary vibrator when loaded by finger (continuous blue line) compared to unloaded conditions (dotted red line). These measurements were obtained using a spectrum analyser (SA).

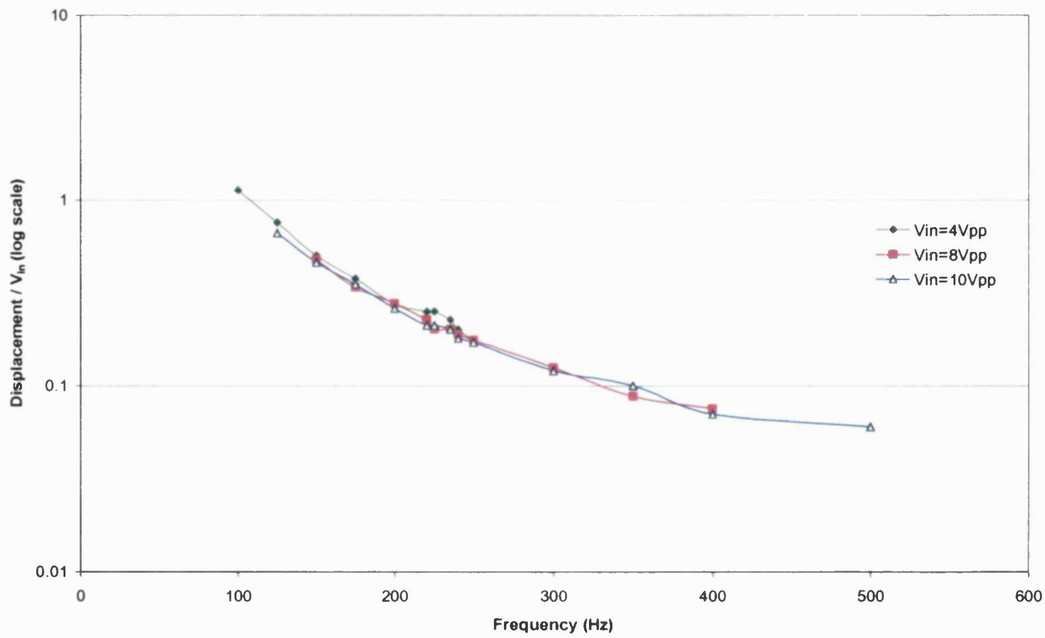


Fig 5.10: Frequency response of the rotary vibrator. Data from measurements made under the microscope. These data show a similar pattern to those measured by spectrum analyser. The three distinct curves show data from tests at three different intensities.

5.4.6 PMD and the perpendicular vibrator

As noted in Section 5.4.4, the approximately linear behaviour of the PMD during the test on the rotary vibrator eliminates the need to perform a similar test on the perpendicular vibrator. However, the remaining tests relating to noise which were carried out for the rotary vibrator need to be performed again for the perpendicular vibrator. The procedures followed to measure these factors were similar to those discussed for the rotary vibrator, with the exception that the cross talk was measured at 15dB SL.

The results show lower level of harmonic components for this vibrator compared with the rotary vibrator. The amplitude value of electrical harmonics within the signal was always lower than –25.9dB SL, and showed its highest value at 25Hz.

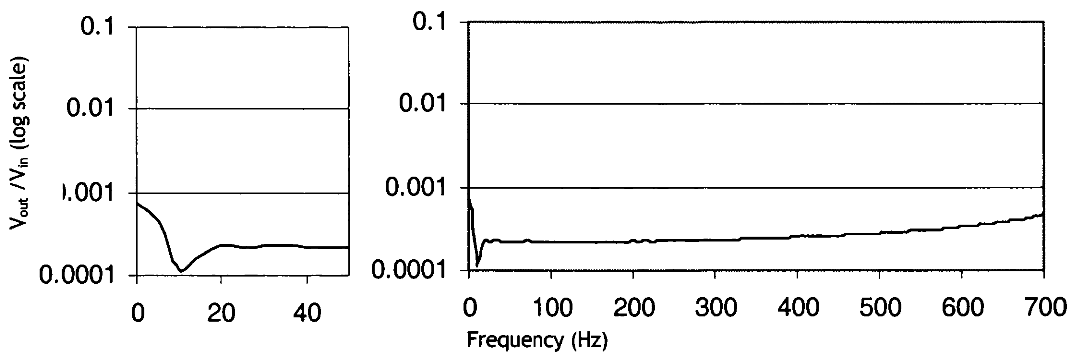


Fig 5.11: Frequency response of the perpendicular vibrator. The graph on the left magnifies the uneven portion of the graph on the right.

The cross-talk between the perpendicular vibrator and the PMD was less than -110dB. This low value of cross-talk is a result of precautions taken during the construction of the perpendicular vibrator which are essential since a smaller range of displacements would be expected to be measured in the case of the perpendicular vibrator[ℜ].

Figure 5.11 shows the frequency response of the perpendicular vibrator measured by the spectrum analyser. The perpendicular vibrator shows much flatter response compared with the rotary vibrator. In a similar manner to that of the rotary vibrator, during the "system calibration" stage, an inverse filter based on these data was applied to input signals to the vibrator in order to correct its frequency response.

The last test on the perpendicular vibrator in relation to the PMD estimated the behaviour of the perpendicular vibrator over the intensity range (input/output response). This has been done in two ways: 1) at lower

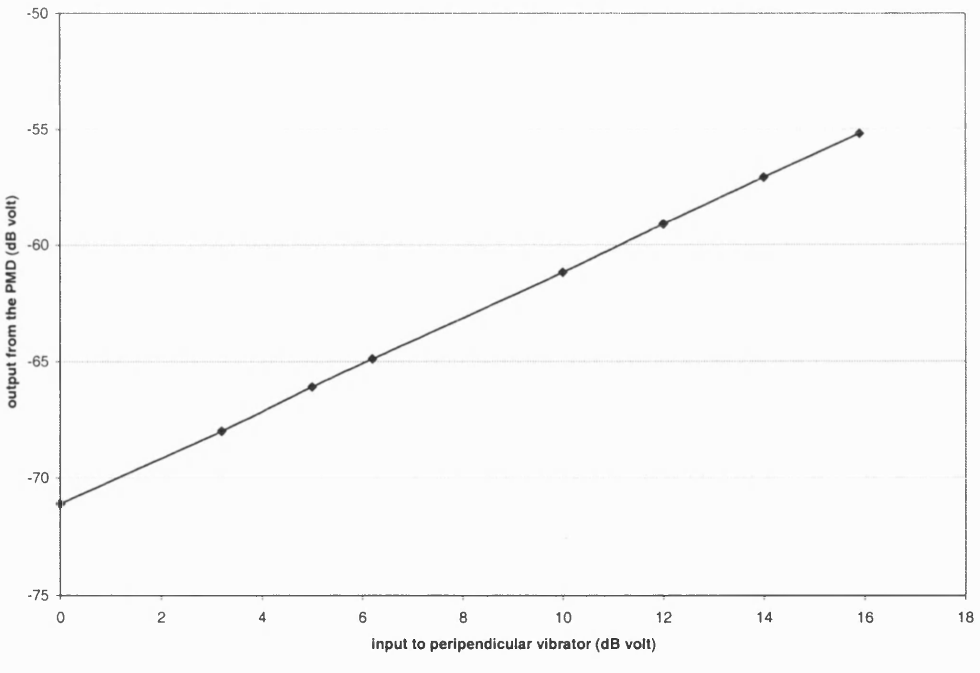
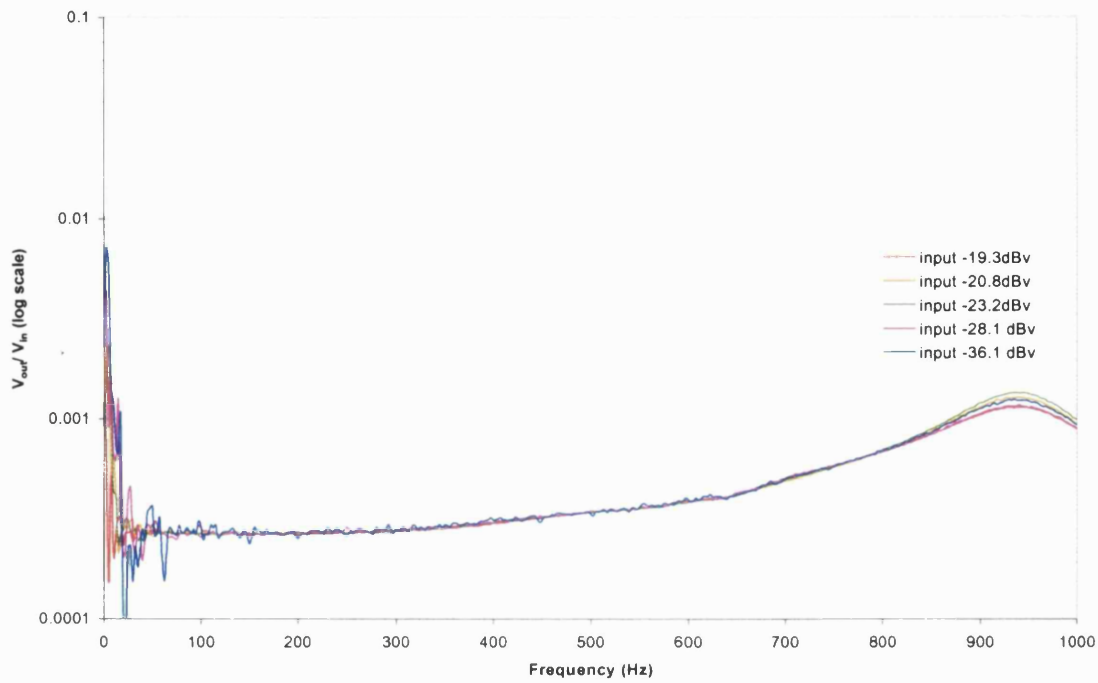


Fig 5.12: The linear relation between the displacement of the perpendicular vibrator and the corresponding voltages from the PMD when both are presented in dB. Inputs were digitally generated sine-waves (as were used in the psychophysical test). The test was performed at 300Hz with the test range corresponding to about 17dB SL for the perpendicular vibrator.

ℜ In the rotary vibrator the relative displacement of the vibrator was magnified for the PMD to measure by placing the PMD at a larger distance from the rotary axis.

intensities, by applying white noise; 2) at higher intensities, by increasing the input to the vibrator and measuring the corresponding voltages output from the PMD. Figure 5.12 shows an example of the results from a test performed by the second method at 300Hz. This graph shows that the output voltage is proportional to the k^{th} power of the input voltage, where k is the gradient of the straight line. The data obtained in this experiment imply that the value of k for this perpendicular vibrator is 1.0, indicating that the output voltage is directly proportional to input voltage in this case. Figure 5.13 summarises the results of the measurement from spectrum analyser.



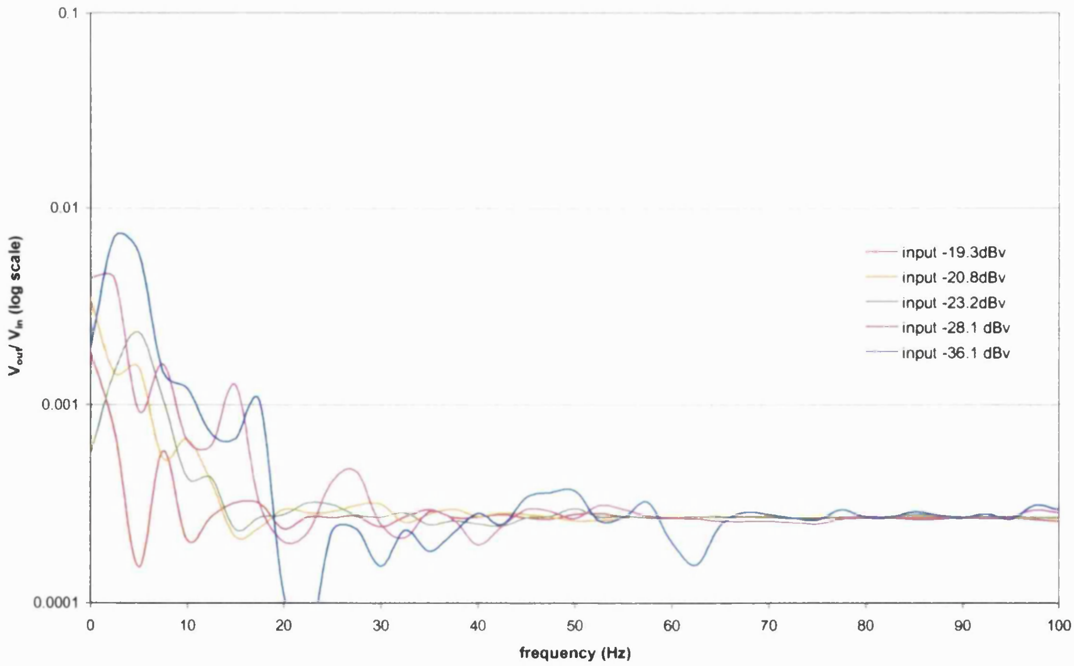


Fig 5.13: Relation between the input to the perpendicular vibrator and the corresponding recorded output voltage from the PMD. At very low intensity and low frequency the system becomes unstable. The graph at the bottom magnifies the uneven portion of the graph on the top.

5.5 Connections

This section describes the remaining hardware including all the equipment used in the psychophysical experiments. It is divided into two parts, driving equipment and masking equipment.

5.5.1 Driving equipment

All the stimuli were computer generated. Different components and their interconnections are illustrated in Figure 5.14. The stimulus could be played out separately from two channels of a 16-bit D/A converter (DA3-4 Tucker-Davis Technologies) or alternatively from two channels of a 16 bit sound card (SoundBlaster 16). The reason for this will become clear after the software is described. Output signals from the D/A converters were electrically mixed (SM3 - TDT) before being independently adjusted in level by a computer-controlled attenuator (PA4 - TDT). The signal was then amplified (Yamaha P1200) and sent to a sound-treated room where it was fed to the vibrators. Further technical details of each piece of equipment comprising the driving system can be found in Appendix 3.

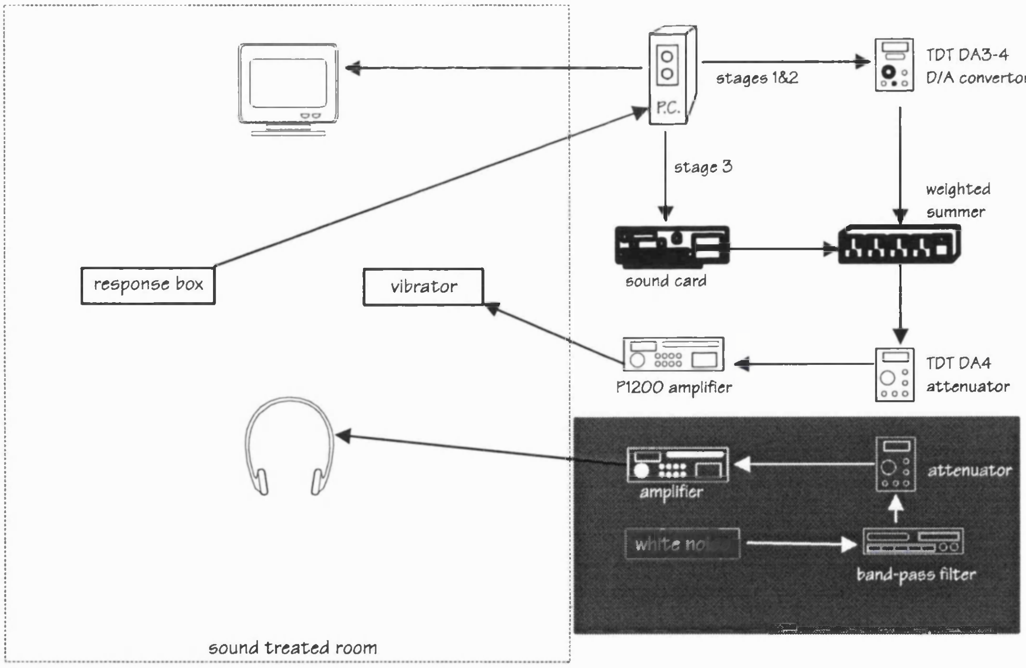


Fig 5.14: Connections between the equipment used in the psychophysical tests.

The response of the subject was also logged and recorded by computer. For this a specific response box was designed and built. The response box was ergonomically constructed so it could be operated by one hand. It had an overall dimension of 120×27×30mm with two response-switches and their appropriate LEDs mounted on its facing surface and a third switch mounted on upper smaller side of the box. The purpose of the third switch is to control initiation and termination of the program.

Response switches were positioned for comfortable operation by thumb. Further, the specific distance between the two switches assured a comfortable resting point for the thumb, important in preventing fatigue (Figure 5.15). The two signalling LEDs were also mounted furthest away from the thumb resting point to prevent ambiguity in signalling and their obstruction by a finger during a test. The tips of these LEDs were filed to create a matt surface and improve the viewing angle. Finally, the selected long-life low-profile switches further improved the operational reliability and comfort of the subject.

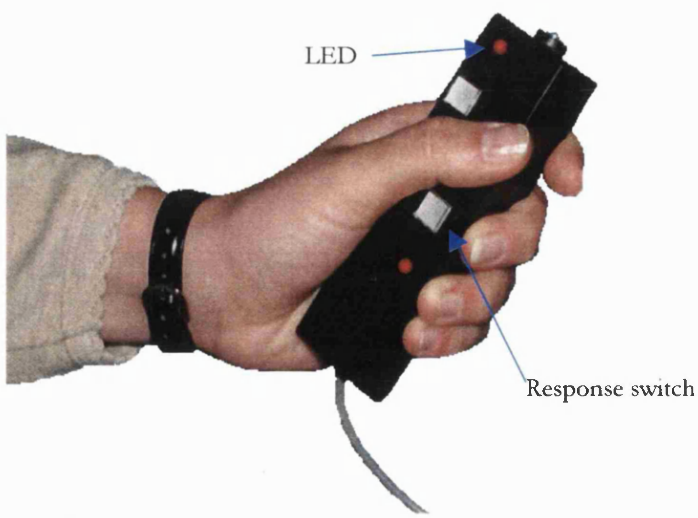


Fig 5.15: The response box designed and used during this study.

5.5.2 Masking equipment

In order to prevent the subject from hearing the sound generated by the vibrators, sound signals were both attenuated and masked. The system comprised a white noise source, band-pass filter, amplifier and a headset (accompanied by a pair of earplugs) connected together as illustrated in the grey part of Figure 5.14. The detailed specification of the first three items is included in Appendix 3.

The selected headset (made by PELTOR) is a set of earmuffs with built in speakers, offering minimum attenuation of 22dB (at 50Hz) and a maximum speaker volume of 82dB (A). The white noise played through the headset speakers improves sound isolation by masking environmental sound while the muff attenuates these sounds. To protect against an uncomfortable level of masking noise from the speakers, earplugs were used. The earplugs offer an average of 31dB attenuation for low frequencies (LASER LITE-LL-1 and E.A.Rsoft).

5.6 Conclusion

This chapter described the development of actuators, their frequency and intensity characteristics, calibrations and their connection to their driving system. The next chapter will focus on the psychophysical tests in which these devices were used. Since the software that controls the equipment is closely linked with the psychophysical procedure, it will be explained in the next chapter.

CHAPTER 6

PSYCHOPHYSICAL PROCEDURE AND RESULTS

6.1 Introduction

This chapter describes the procedures, calibration and results from psychophysical measurements. The psychophysical measurements were performed in three stages, hence will be described under three separate sections. Each section first describes the aim of the particular stage, followed by a description of the software for that specific task. System calibration is described, followed by the results from the psychophysical tests.

6.2 Psychophysical procedures

The overall aim of the psychophysical tests is to evaluate the level of interaction which takes place between waves propagating within the skin. Conceptually, these waves can interact with one another if they are propagating in the same plane (see Section 4.4). The way the interaction was evaluated will be explained further under Section 6.2.4. During its two preceding stages, the absolute threshold of the subject is established and the level of signals at intensities higher than threshold for both types of vibrator is subjectively equated.

6.2.1 Common procedures

In order to make the experimental measurements desired in the time allowed, neither temperature nor initial force was controlled and no surround was used. Signals applied were computer-generated sine waves sampled at 10kHz with their details described under each stage. The order of presentation was randomised and the response rate of subject was not considered important. Subjects always wore earplugs and headphones (described under Section 5.5.2) supplied with white noise band-passed between 70-5000Hz. (except for the pilot study - Section 6.4.1). When the noise was switched on, its level was raised gradually (over a period of 10 s) from 50dB SPL to 92dB SPL to improve the comfort of the subject. Subjects were requested to relax and remove their finger from the vibrator in the intervals between tests at each frequency, and to feel comfortable to leave the test room whenever they liked. In addition, all tests were performed at the same time of day (10 AM ± 1 hour) and always with one to three days interval between each test to prevent fatigue (except for subject "A"). These three precautions were expected to reduce the variation in the threshold measurement due to viscoelasticity of the skin and tiredness. They were always provided with writing tools during each session to note any comments (*e.g.* quality of stimuli). These comments proved valuable (at least) in tuning the details of the psychophysical test. Note also that the reported values in the frequency range are the result of interpolation of measurement at eight set frequencies (25, 50, 100, 200, 250, 300, 400 and 500Hz) which henceforth will be referred as a "complete set" of tests. The rise/fall time of these stimuli was kept constant at 120ms during all three stages while the duration of stimuli was increased during stage 3.

6.2.2 Vibration threshold (stage 1)

During this stage, the threshold of vibration for sinusoidal waves at the eight pre-set frequencies, for both the perpendicular and rotary vibrators, was established. A two- interval, two-alternative forced-choice adaptive paradigm was used to estimate the 79% point on the psychometric function. Levitt's (1970) transformed up and down procedure was used with an initial step size of 10dB, which was reduced to the final size of 2dB over the first 3 reversals. The value of the threshold at each frequency was calculated by averaging the result of the last six reversals at the final step size. The time waveform of the stimuli consisted of a 1000ms steady-state portion and 120ms raised-cosine onsets and offsets. This length of time was considered adequate to provide both a sufficient period of presentation of stimuli and to minimise adaptation (see Chapter 3). Subjects responded with buttons on a response box (described under Section 5.5.2) equipped with two LEDs indicating the presentation intervals and providing feedback. The stimulation site was the anterior distal part of the right hand index and middle fingers (first phalanx).

Software

The stage one procedure was controlled by a modified version of software developed earlier by Prof. S. Rosen for the purpose of hearing research. The software generates a sine wave with a predetermined raise and fall time and provides control over various parameters. At termination, the software generates a log file stamped with date and time, detailed information regarding the presented stimuli and the corresponding responses of the subject followed by the estimate of the threshold.

Modifications to the software were aimed at reducing operator error and to facilitate both running the test and collecting the results. The initial screen was replaced by a screen which required different and fewer number of parameters to be specified (subject and type of vibrator only). A warning then was given to the operator to specify the amplification gain (to be set on the Yamaha-P1200 amplifier – see Figure 5.14) according to the type of the vibrator in use. This warning was important considering there is over a 30dB difference between the operating voltage of the two types of vibrator in use. Then followed a set of 8 tests, at eight chosen frequencies in a random order (a complete set). Their initial intensity was always higher than threshold and corrected according to the measured frequency responses of that particular device (data from Sections 5.4.5 and 5.4.6). Upon the completion of the threshold measurement at each frequency, the program paused and awaited re-starting by the subject (the third switch on the response box) – this provided a rest period for the subject. Finally the information entered on the first screen was used by the program to classify the result of each subject according to name, type of vibrator, date and the number of the test on that day.

6.2.3 Subjective equality (stage 2)

During this stage, the perceived strength of one vibrator (*i.e.* perpendicular) was subjectively equated to the perceived strength of the reference (rotary) vibrator for intensities of 5, 10 and 15dB above the established threshold (*i.e.* dB SL) from stage one. A two-interval, two-alternative forced-choice adaptive procedure was employed to estimate the 50% point on the psychometric function (final step size 2dB). In the course of each interval, a stimulus was sent to each of the vibrators in turn. Subjects were required to indicate which of the two intervals felt more intense. While the order of presentation was random, the stimulus to the rotary vibrator was always at the set intensity and the response of the subject controlled the intensity of the perpendicular vibrator. The stimuli were similar to what was used in stage 1, and feedback was provided through the same response box. The stimulation site was the anterior-medial- distal part of the right hand index and middle fingers for the perpendicular and rotary vibrators respectively.

Software

The same software described under the previous stage, with further modifications, was used here. The modified software used the subject's absolute threshold from the previous stage, and generated two independent sine waves - which hereinafter will be refereed to as "standard" and "comparison"- controlling the level of the comparison according to the subject's response. The rest of the modifications were similar to those described under stage 1. The output from this stage was available to the next stage in the form of a text file

6.2.4 Interaction test (stage 3)

This stage of the psychophysical test is aimed at evaluating the level of interaction between two vibrators working in proximity to each other The interaction between a pair of vibrators of the same type (both rotary or perpendicular) will be measured first. This will provide both information as to how the level of interaction is affected by changing only the method of mechanical stimulation of the skin and reference standards for comparison when the interactions between two vibrators of different types are measured.

The evaluation is based on the detection of "beats". Beats are the result of interference of two waves with a slight difference in frequency moving in the same plane. The resultant wave has an effective frequency equal to the average frequency, which is $(f_1+f_2)/2$ and amplitude that varies in time by:

$$A = 2A_0 \cos 2\pi (\frac{f_1 - f_2}{2})t$$

Where A_0 is the maximum amplitude of each wave.

In other words, the beats are felt as a cyclic change in amplitude at a rate equal to the difference frequency of the two primary sinusoids.

The level of interaction was evaluated by selection of the stimulus frequencies in a way that caused the generated beats (interacting waves) to fall into a range distinguishably different from that of the causal waves. The results of a pilot study showed that beats with frequencies between 2-3Hz are the most convenient to be detected by the subject. Beats with frequencies lower than 2Hz are habitually mistaken for the subject's own heartbeats, felt at the body's contact point with the vibrator. Beat rates of higher frequency are also difficult to identify. As a result, a 2Hz frequency difference between the two stimuli was selected for stage 3.

A two-interval two-alternative forced choice test without feedback was implemented in this stage of the test. During each interval, two simultaneous sinusoids were presented on two vibrators, which were either 2Hz different in frequency or were the same. A total of 16 responses was recorded during each run. Each pair of vibrators was placed on the same finger used during stage 2 and on the same area of the finger but on the lateral sides instead of the medial section. The distance between the vibrators was always constant and equal to 1 ± 0.1cm. The order of presentation was randomised with an equal chance of presentation for each of the four different trial types (Figure

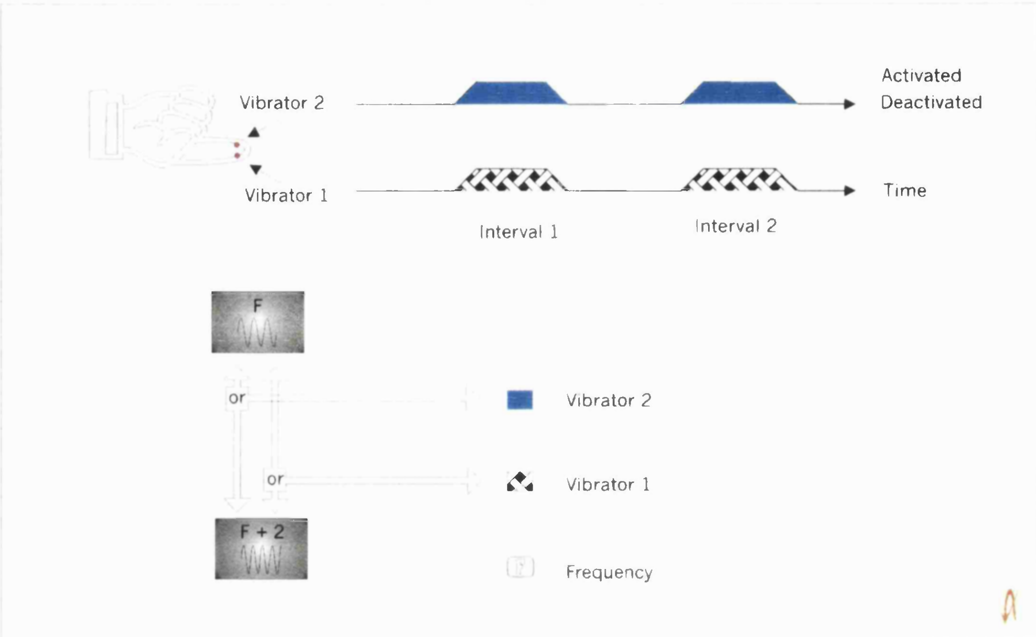


Fig 6.1: Showing the order of presentation of stimuli for the interaction test. Stimuli to each vibrator at any time have a frequency of F or F+2Hz, see lower section of the figure. The upper section shows the timing of the stimuli and the test-site (not to scale).

6.1). The subject responded through the keyboard by keying "s" and "d" for "same" or "different" respectively. Unlike the other two stages, the output from this stage was through a SoundBlaster sound card and stimuli had a duration of 4000ms (instead of 1000ms used in the other two stages) to facilitate the detection of beats.

Software

Completely new software was developed for this stage of the psychophysical test, using DOS batch scripts and a C program. The program commenced by the experimenter entering three types of information into its first screen, including the name of the subject, the type of vibrator under test and a code, reflecting the date and the number of test. The program accessed the subject's results from the previous stage (in text format) to adjust the level of the output signal. The intensity of each channel was controlled independently allowing the same software to be used for further psychophysical tests where two different types of vibrators may be used. Results were presented in the form of a text file and saved automatically.

6.3 System calibration

In addition to the calibration of each device described under Section 5.4, the system required an overall calibration so the recorded values from subject's responses under each stage could be referred to a standard scale.

Three points emphasise the importance of this calibration: a) there is a disparity between the output of the two channels of the software used in stage 2, estimated to be about 29dB, which originated from the task the unmodified software had to serve; b) the output voltage from the D/A converters differ in stage 2 and stage 3 *i.e.* SoundBlaster card and TDT DA3-4; c) the required voltage to drive the two types of vibrator during the test can vary by as much as 110dB. This value was established during the threshold test, and is the threshold of sensation for the perpendicular vibrator at 50Hz relative to the rotary at 200Hz. The overall calibration aimed to reduce distortion by setting all devices in mid range for any particular test.

Since performing the system calibration is unavoidable, during the same process the response of the vibrators will also be corrected by applying their frequency responses provided by the PMD (see Sections 5.4.5 and 5.4.6). Note that the correction of the frequency response is not necessary for performing the interaction test but is essential for comparison and analysis of data from the two types of vibrator. Note that the y-axis of results corrected for frequency response will be shown by the unit of "relative displacement-dB" and not simply to input voltage. The word "relative" implies that the value of each point on a graph from a complete set of tests is expressed in relation to the value of the other points on the same graph .

The sequence for system calibration started from stage 3, then stage 2, and finally stage 1. Upon its completion, the value of zero in an input file to any of the three stages will result in an equal output voltage from each channel. Voltages - during all three stages - were measured at the frequency of 200Hz at the constant sampling window by a calibrated ONO-SOKKI spectrum analyser model CF-3502. The procedure for "system calibration" was as follows:

1) In stage 3, the amplification gain of the sound card was set slightly higher than the mid-power point (-3dB) and the channels were balanced (these adjustment were set to be initiated upon every boot up). Input text values to stage 3 (at 200Hz) were set to zero and this was confirmed by the TDT attenuator being turned to zero.

2) The gain of the power amplifier (Yamaha P1200) was set to drive the perpendicular vibrator at its peak power.

3) The output voltage for 0dB attenuation, when the Yamaha amplifier was set at (-6dB) was measured and this value (equal to 36.1 ± 0.2dB volt) was taken as a reference voltage.

Following this procedure the calibration factor within the program under stages 1 and 2 was set to a value to generate the same output voltage from their channel "B"– see Figure 6.2.

Due to the fact that the software used for the first two stages was a modified version of software originally developed for a very different task, the path of calibration for channel "A" was slightly longer.

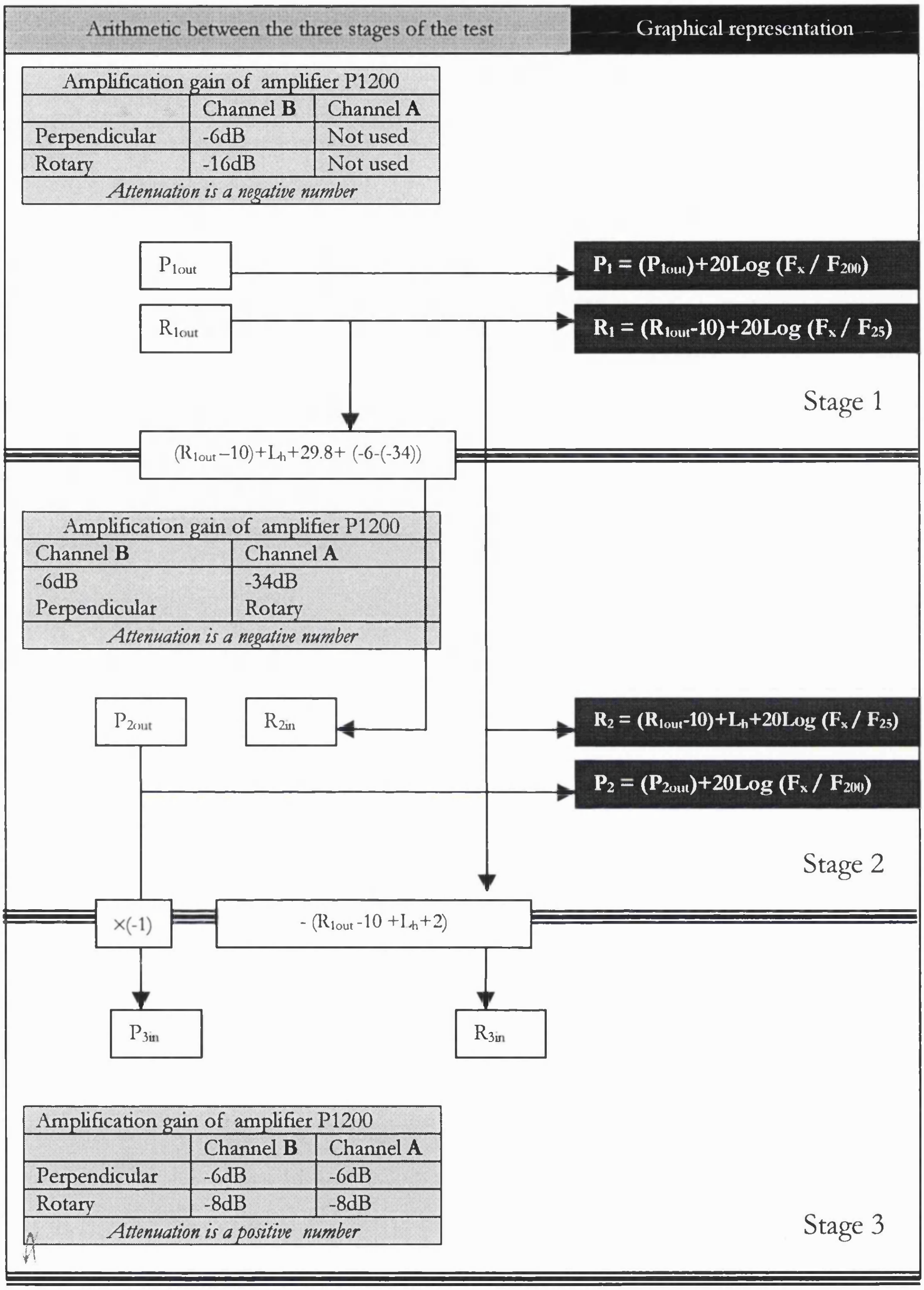


Fig 6.2: Adjustments between the three stages of the test to correct the values of each stage to a value referenced to 36.1dB volt. L_{th} reefers to a level higher than threshold and 29.8 is the difference between channels A and B. Graphical representation of the result for the first two stages are provided by adding the inverse filter made from the responses of the two types of vibrator measured during the construction process.

The use of channel "A" was completely avoided during the stage 1 and both types of vibrator *i.e.* perpendicular (P) and rotary (R) were initiated through the channel "B", although this was not a solution for stage 2 of the test.
Measurement showed that the output of channel "A" was 29.8dB lower than channel "B". Although this appears an ideal coincidence - as the required voltage to drive the rotary vibrator (see Sections 5.2 and 5.3) was almost the similar factor lower than needed for the perpendicular vibrator - the range of the accepted input values for these two channels by the program were different.
The required arithmetic to re-scale the values to the correct output was performed in a spreadsheet program and facilitated by the use of *macros*. Macros were invoked to automate the task of taking the inputs and generating a number of output files (in a text form). This relatively simple approach provided certain advantages compared to alternatives such as C-programming. First, the calculation between the different stages could be carried out in a single page facilitating data rechecking. Second, data input to the spreadsheet could be readily presented graphically and third, having each subject's data in a single application facilitates the handling and interpretation of final results. In summary, it was believed that this approach would reduce the chance of human error (keying in the data /programming) and creates an environment where data could be easily rechecked. Figure 6.2 shows the overall view of the adjustments carried out within the spreadsheet section of the program.

6.3.1 Simulated test

A simulated test was performed to check the system calibrations prior to the collection of data from the subjects. In this test a value within the acceptable range of the program was entered into the stage 1 and through all subsequent stages the measured values were compared to the expected values. Figure 6.3 explains this procedure by means of an example. In this example value (-40) was entered to the stage 1 rotary vibrator.

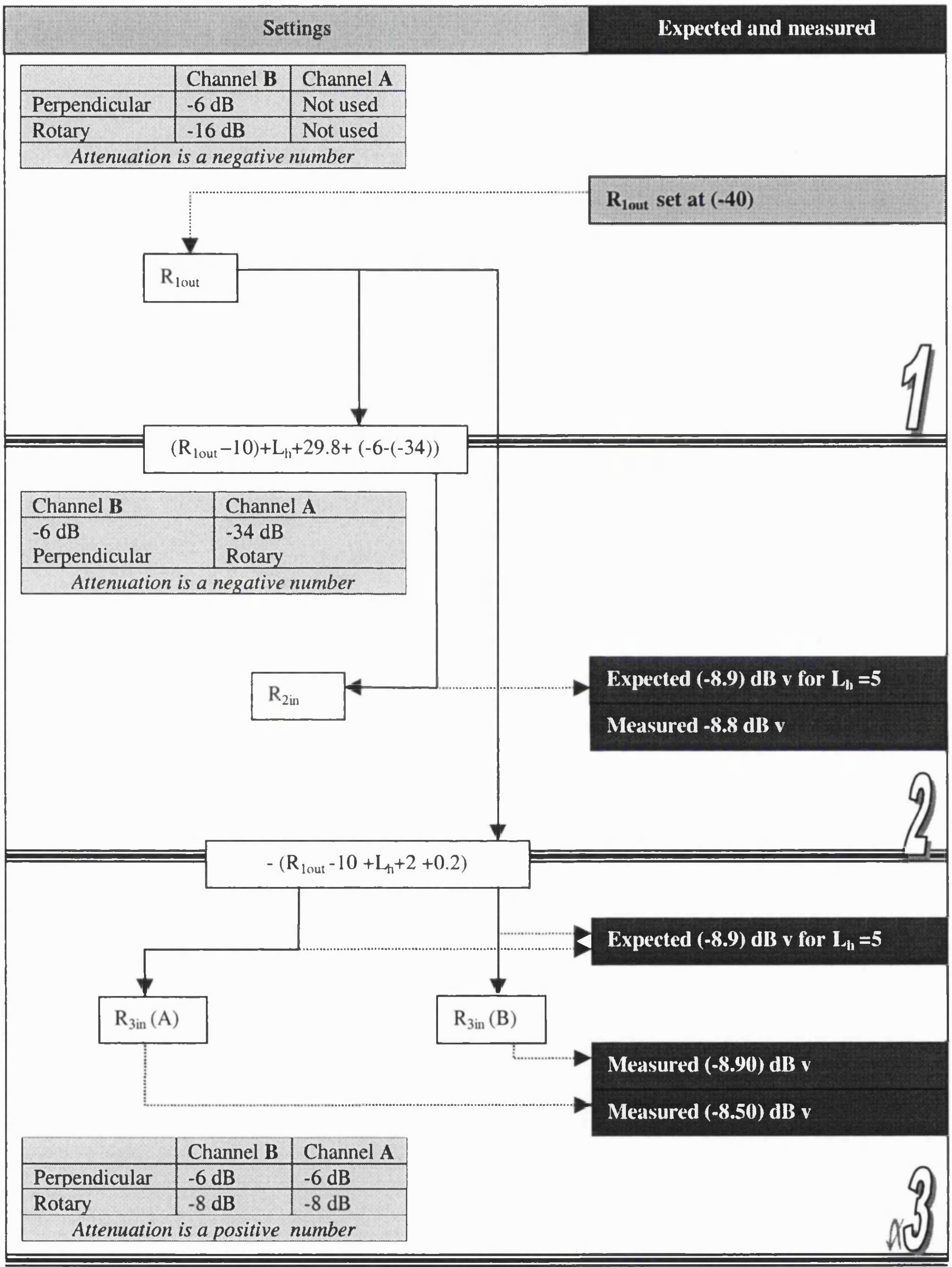


Fig. 6.3: Graphical representation of the simulated test. Note while the values of dB volt carried between different stage are intended to be kept invariant, the input and output values negotiated within the program vary considerably.

At 5dB higher than threshold, this value is expected to produce -8.9dB volt (36.1+(-50)+5 ref. to 36.1dB volt) in the output of channel "B" stage 2 for the rotary vibrator and a similar value at the outputs of both channels in stage 3. Measurement confirms -8.80dB volt at stage two and -8.67 and -9.10dB volt (channels A and B respectively) at stage 3, assuring the correctness of values passed to these stages by the program within the error range.
The simulated test was repeated occasionally during the testing period and proved invaluable both in confirming the correct operation of the system and in locating any possible faults. An example of its usefulness was detection of swapped TDT attenuators between the two channels on one occasion.

6.3.2 Error range of the driving system

The programs for the first two stages of the test can be calibrated within 0.1dB accuracy. The mechanically controlled attenuator in the final driver amplifier introduced a further ±0.3dB error, bringing the total error to 0.7dB. Despite changes in hardware during stage 3 the calculated error range does not alter greatly. During stage 3, the error of the final amplification has reduced to 0.2dB while the SoundBlaster introduced a further 0.5dB variation along the frequency range considered in this study. This brings the total error for this stage to about the same range as the other two stages.

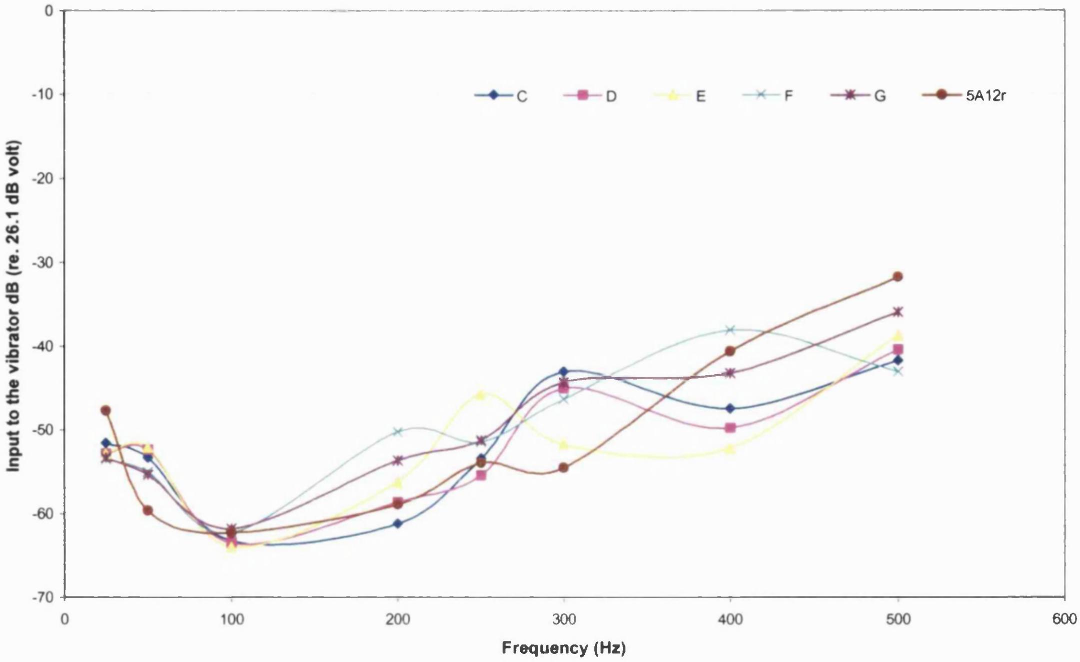
6.4 Psychophysical results

6.4.1 Pilot investigation

A pilot study was carried out to evaluate the performance of the complete system on one subject (A - the author). This investigation was also expected to reveal important issues for the evaluation which perhaps were overlooked. Note that during the pilot study the bandwidth of the masking noise was between 70 and 800Hz. Data to specify the absolute threshold was collected after completion of two complete sets of tests on the rotary vibrator, which were considered as training (data shown in Appendix 4, Table 1, sets A and B). Since the recorded values from the first three completed sets following the training were inconsistent, a further three complete sets were conducted.

Data from these six complete sets of tests show their highest standard deviation at frequencies of 400, 300 and 500Hz (σ=3.1, 2.4 and 2.3 respectively) and their lowest standard deviation at frequencies of 100 and 50Hz (1.2 and 1.4). The result of these data summarised in the top graph of Figure 6.4.

A similar test was performed using the perpendicular vibrator. The absolute thresholds measured by using the perpendicular vibrator are not necessary for conducting the next stage of the test *i.e.* subjective equality test. These tests were performed mainly to investigate the similarity of thresholds from the perpendicular vibrator and rotary vibrators. Eight complete sets of tests were performed on subject "A". The results of these tests are shown in the lower graph of Figure 6.4 (data shown in Appendix 4 - Table 2). Initial examination of these data suggests a higher variation among absolute threshold curves for the perpendicular, as compared to the rotary vibrator. This is despite the similarity between the range in which the standard deviation of data points from these two types of vibrator lies. Since the threshold of sensitivity is considered a milestone against which other measurements will be evaluated, this higher variation for the perpendicular needed to be explained. It was speculated that the inconstancy in the recorded thresholds is due to test conditions in which the temperature and static force were not controlled (Section 6.2.1), although this would not explain why the level of this inconsistency is different for the two types of vibrator. Since the inconsistency was greater for the perpendicular vibrator and at higher frequencies, two possible causes were investigated: 1) the possibility of auditory cues 2) the possibility of vibrations being passed to other body locations. The second possibility is not remote, considering that the reaction forces generated by the rotary vibrator are damped to a greater extent compared to the reaction force generated by the perpendicular vibrator (see Chapter 5).



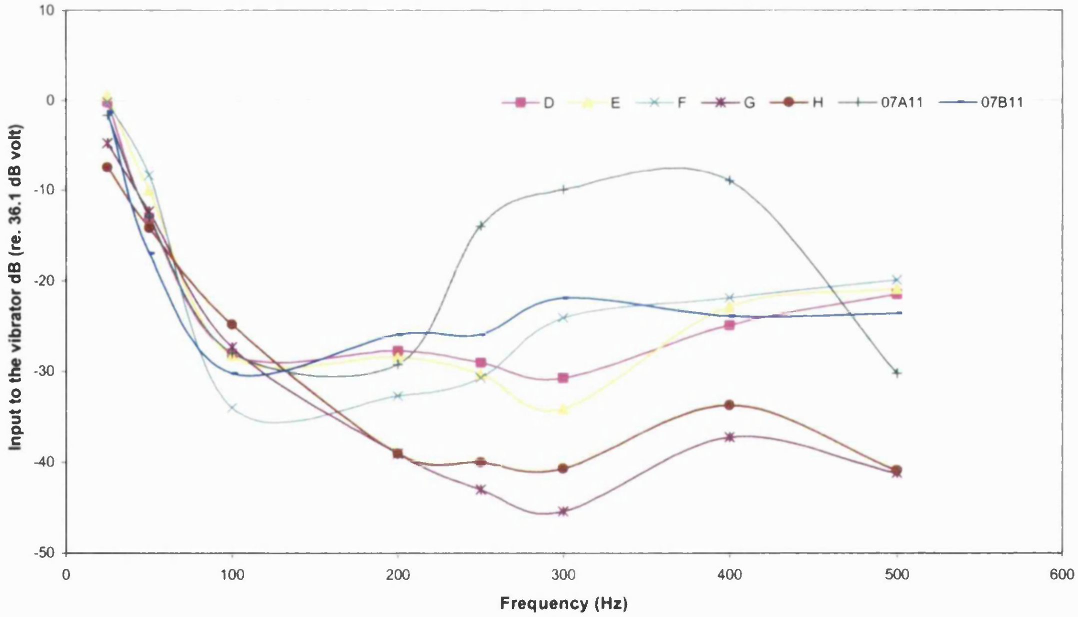


Fig 6.4: Data from the pilot study. Top graph shows the data from six complete sets of tests from the rotary vibrator. Lower graph presents the corresponding data from the perpendicular vibrator. Note that data points are only related to the absolute threshold and are presented in this form only to compare the data from the same type of vibrator.

Two modifications were performed on the test procedure to exclude these possibilities. 1) The arm-resting place was separated from the desk on which the vibrator was placed and held on a separate stand. This precaution should prevent any vibration that may not have been damped by the heavy mass of the vibrator to be passed to the subject (for discussion, see Section 6.5). 2) In addition, the upper frequency of the masking noise was increased from 800Hz to 5000Hz to prevent the possibility of any auditory clue (from higher harmonics of the wave). This was followed by four complete sets of tests on the perpendicular vibrator to evaluate the effect of the modifications. Figure 6.5 shows the summary of the results, demonstrating a clear improvement to the previous set of data (lower graph of the Figure 6.4). The second set of data will be used for subject "A" throughout the rest of the study (details in the Appendix 4, Table 3).

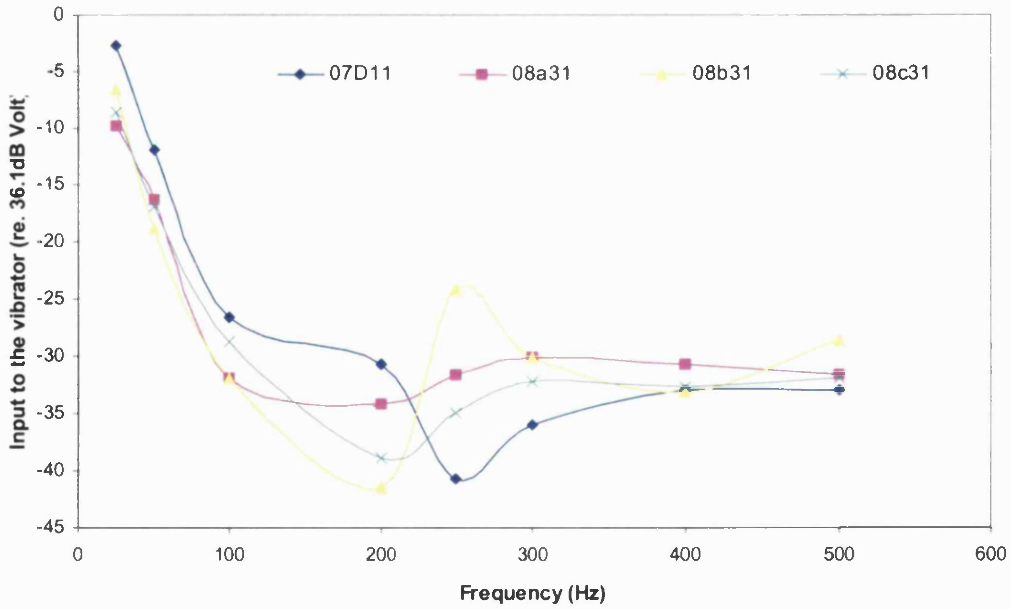


Fig 6.5: Pilot study for perpendicular vibrator after modification of test procedure. The results of four complete sets of tests by subject "A".

The second issue in the pilot study concerned the subjective equality test (stage 2). Since it was not possible to place both types of vibrators simultaneously at the same body location, they must be placed at two different locations. However, if the threshold and the perceived strength of stimuli at suprathreshold levels at these two locations are not equal, it creates an unequal condition for the comparison of the two types of vibrator. Before introducing ways to overcome this problem, it is reasonable to evaluate the level of this difference.

Data was collected by performing absolute threshold tests on the index and middle fingers of subject "A" using the rotary vibrator. Having learned from the earlier experiments and observed the variation in recorded threshold even among the tests performed in the time span of a few hours, these tests were performed in the following order. First, two samples at different frequencies

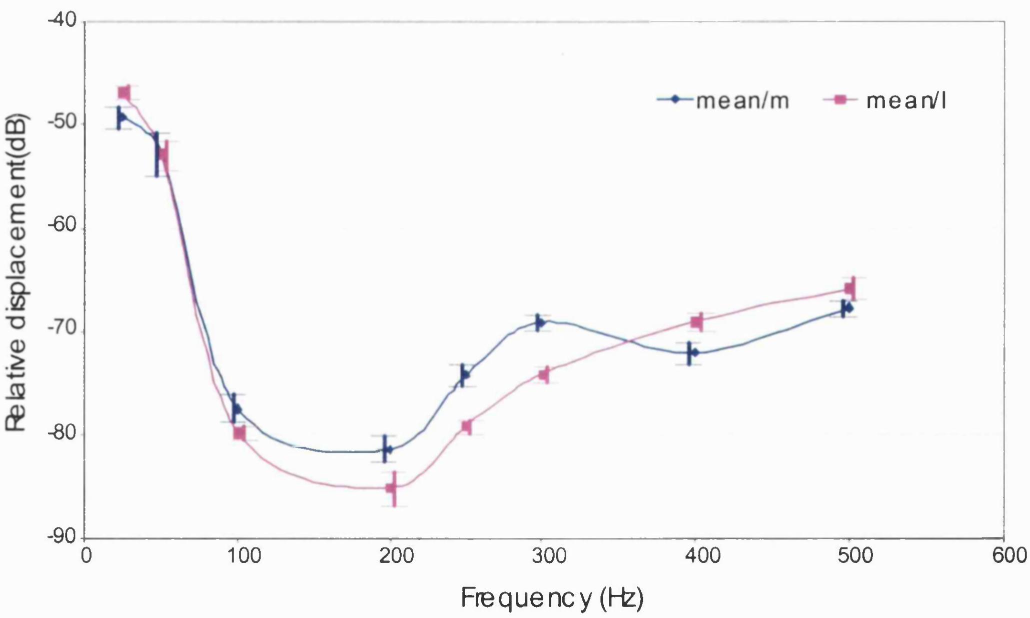


Fig 6.6: Rotary vibrator - mean of the two complete sets of the absolute thresholds from index (I) and middle (m) finger as a function of frequency- subject "A". The vertical lines show ± SD.

were taken from one finger and then the procedure was repeated on the other finger at the same frequencies (*i.e.* 100Hz, 200Hz index; 200Hz, 100Hz middle finger and so on). This precaution was expected to minimise the effect of uncontrolled parameters by shortening the time between sampling from each finger and yet maintain the randomness of the process. Figure 6.6 shows the average of two complete sets of tests performed in this manner.

Visual comparison of these data with the data acquired when one finger was used suggests little difference between the threshold of sensitivity of the index and middle fingers. Using a paired sample t-test for means, the two data sets were also found not to be significantly different ($t(7) = -0.90, p = 0.39$).

Analysis of data from these two fingers also show that during both sessions the threshold of detection of the index finger was lower than the middle finger at frequencies of about 200Hz and higher at frequencies of about 450Hz (details in Appendix 4, Table 4). Furthermore, the absolute thresholds for both fingers measured in the second session were lower than the

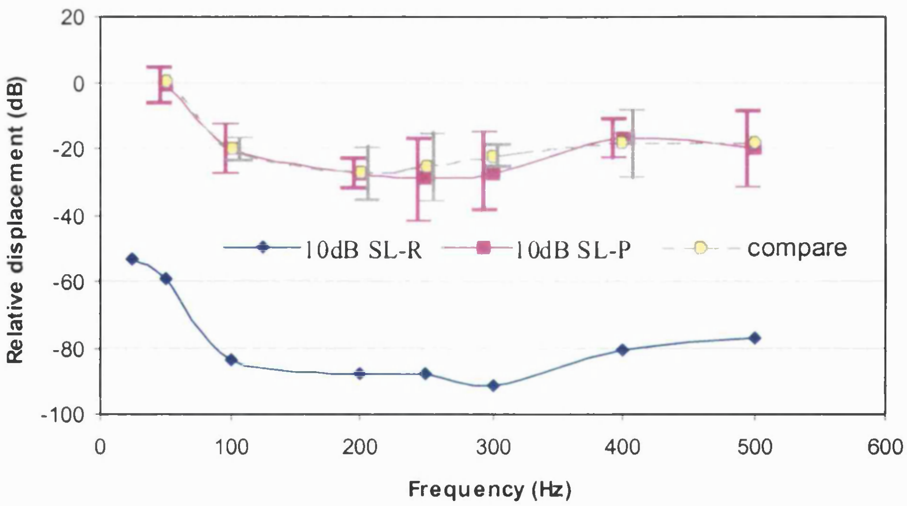


Fig 6.7: The level of the perpendicular vibrator on the index finger needed to match the perceived level of the rotary vibrator at 10dB SL on the index finger, presented at the middle finger (upper continues curve). The dotted line shows the result of a similar test under the standard condition *i.e.* against 10dB SL on the middle finger, presented at middle finger. The lower curve shows the 10dB SL rotary at index finger that was presented as standard stimulus at the middle finger. The vertical lines show ±SD

corresponding measurement from the first session. This latter point suggests a consistency in the difference of the thresholds recorded from index and middle fingers, which is not an error of measurement.

The matter of equality or inequality of the absolute threshold of index and middle fingers was further investigated by analysis of the data gathered in completion of stage 2. This evidence will be presented here, being more relevant to the current discussion.

During stage one, the absolute threshold for the rotary vibrator for subject "A" was estimated for both middle (as in the original scheme) and index fingers. Later during stage 2, the extra set of data (from the index finger) was used to set the levels for stimulation of the middle finger. Then the normal procedure for determining subjective equality for the perpendicular vibrator at the index finger was performed. If the absolute threshold for middle and index finger are similar, it is expected that the subjectively equated curve for the perpendicular with any of these two alternative forms of rotary threshold to be similar too. Figure 6.7 summarises the results of five complete set of tests by subject "A" in which the measured threshold for the rotary vibrator at index finger was raised 10dB and played at middle finger. The middle finger stimuli was then subjectively equated to the perceived strength of the perpendicular vibrator at the index finger. The superimposed - comparison line - shows the result of the similar test under the standard condition *i.e.* subjective equality of the perpendicular vibrator against 10dB SL rotary at middle finger (data in Appendix 6 - Tables 1 and 2). As a result of these observations, the middle and index finger will not be treated differently during this study.

During stage 3 of the test no complications were observed and the procedure ran as anticipated.

Changes to the experimental procedures, based on the pilot investigation, can be summarised as follows:

- The bandwidth of the masking noise was increased
- The hand and vibrator were isolated by placing them on separate supporting frames.
- The middle and index finger will be treated equally in terms of their detection threshold and perceived strength of stimuli at suprathreshold levels for the purpose of this study.

6.4.2 Vibration threshold (stage 1)

Three subjects – two females, one male (the author "A") - aged between 26-37 participated in the three stages of the test. Subjects had no known history of peripheral or central nervous system disorder or skin conditions. The test procedures used in this stage are similar to those described under Section 6.2. Note that the absolute thresholds presented in this section are measured at the anterior-distal part of the middle finger of the right hand for the rotary vibrator and anterior-distal part of the index finger of the same hand for the perpendicular vibrator. In addition, subject "A" also contributed to tests using the rotary vibrator on the skin site designated for the perpendicular vibrator. This study was approved by the Committee on Ethics of Experimental Procedures Involving Human Subjects, School of Medicine, University College London.

A total of twenty-six complete sets (each with an estimated time of 25 minutes) were performed by the three subjects to evaluate their absolute threshold. The number of tests was not equal for all subjects and was determined by the consistency of their results. Details of the tests are included in Appendix 5. Figures 6.8 to 6.10 summarise the results of these measurements for the three subjects.

As mentioned earlier, only the results of the rotary vibrator are necessary for this stage. A limited number of tests using the perpendicular vibrator were performed to compare the shapes of the absolute threshold curves from the two types of vibrator.

The results were subject to an ANOVA with fixed factors of frequency and vibrator type, and subjects as a random factor. Only the highest order interaction was not significant, but all second order interactions were ($p \le 0.035$). All main effects were also significant, although the effect of subject was relatively weak ($F(2, 3.578)=10.960, p=0.030$).

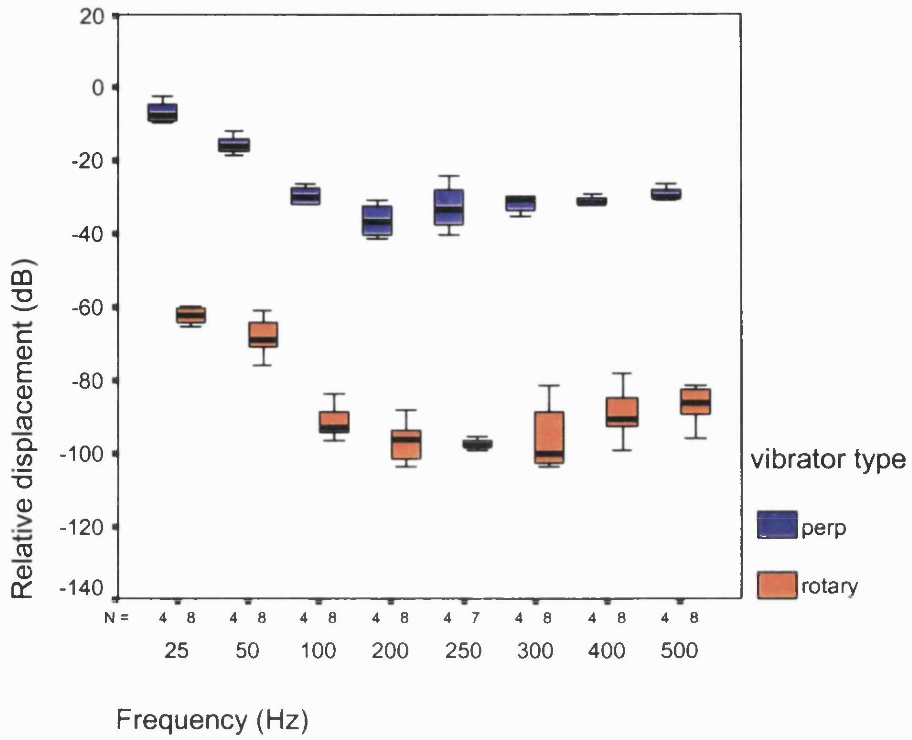


Fig 6.8: Boxplots showing the absolute threshold data for both types of vibrators from subject "A". The small numbers on the x-axis indicate the number of observations that were used to make each "box".

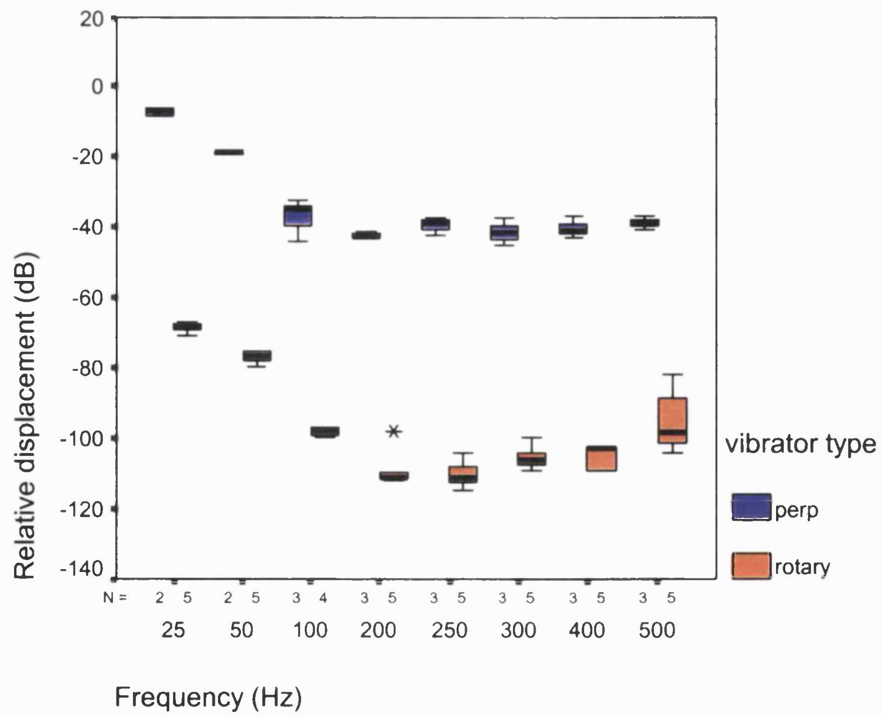


Fig 6.9: Similar to the previous graph but for subject "B". Smaller numbers at some low frequencies are due to responses being out of the dynamic range of the system at those frequencies.

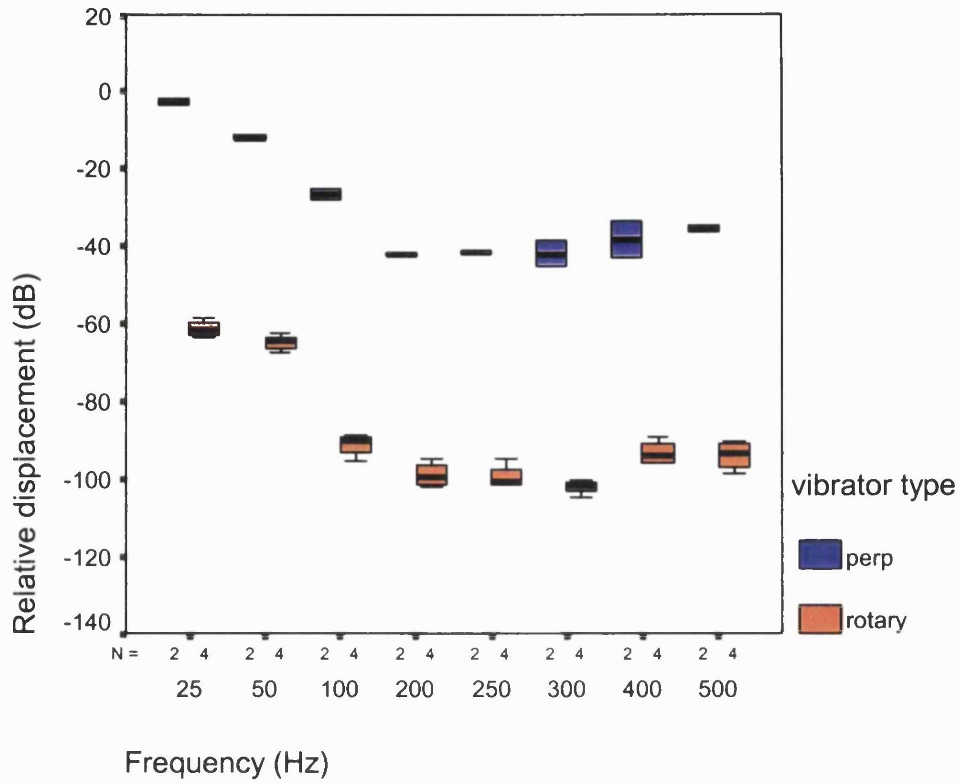


Fig 6.10: Similar to the previous graph, but for subject "C"

Both main effects of frequency (F(7,14.51=82.39, $p<0.001$) and vibrator type were highly significant (F(1,2.041)=1999.5, $p<0.001$). The relationship between factors (vibrator type, frequency and subject) appears complicated. The present of a significant "frequency × vibrator type" interaction indicates that the shape of the curves from the two types of vibrator are not the same (although as shown in Figures 6.8 to 6.10, they are not widely different). The present of a significant "subject × frequency" interaction indicates that the shape of the curves are not the same for all subjects. This effect had the lowest significance level of all the second order interactions (F(14,14)=2.727, $p= 0.035$) and as shown in Figures 6.8 to 6.10 they are not greatly different either. Finally, the existence of a "subject × vibrator type" interaction shows that subjects performed differently for different types of vibrator. Note that none of the observed dissimilarities confirm or reject the possibility of the graphs to be similar at some frequencies.

This will not be examined here for two reasons. First, to be able to specify at which frequency these two graphs are similar, a greater number of observation and better-controlled testing conditions are necessary to eliminate the variability in the data. Second, the real Operation Voltage Difference (OVD) between the two vibrators is needed to be known. Estimating the OVD by the method used here (*i.e.* from the mean difference between the two curves) is not considered appropriate for answering such a question. In brief, the OVD estimated from the mean difference can be affected by the weight of data comprising the two sections of the curve, which are considered dissimilar.

Similarities between the absolute threshold from the rotary vibrator and that of the perpendicular vibrator could in fact suggest that these two types of vibrators are stimulating similar types of tactile receptors (see Chapter 3). In particular, comparison of the data in figures 6.8 to 6.10 with that in figure 3.8 show a good match to the frequency response of the Pacinian receptors. This suggests that the thresholds measured were determined by these receptors.

To enable visual comparison of the threshold curve from each type of vibrator, the average difference between them was removed and data from all subjects presented in Figure 6.11. The median of the values from the rotary vibrator for each subject was passed to the next stage for the "subjective equality" test.

The result of the stage 1 of the test (absolute threshold measurement) can be summarised as follow:

- Subjects differ in their absolute threshold.
- The shape of curve (as a function of frequency) is different for the two types of vibrator, although not greatly so.
- The shape of curve (as a function of frequency) is different for different subjects.

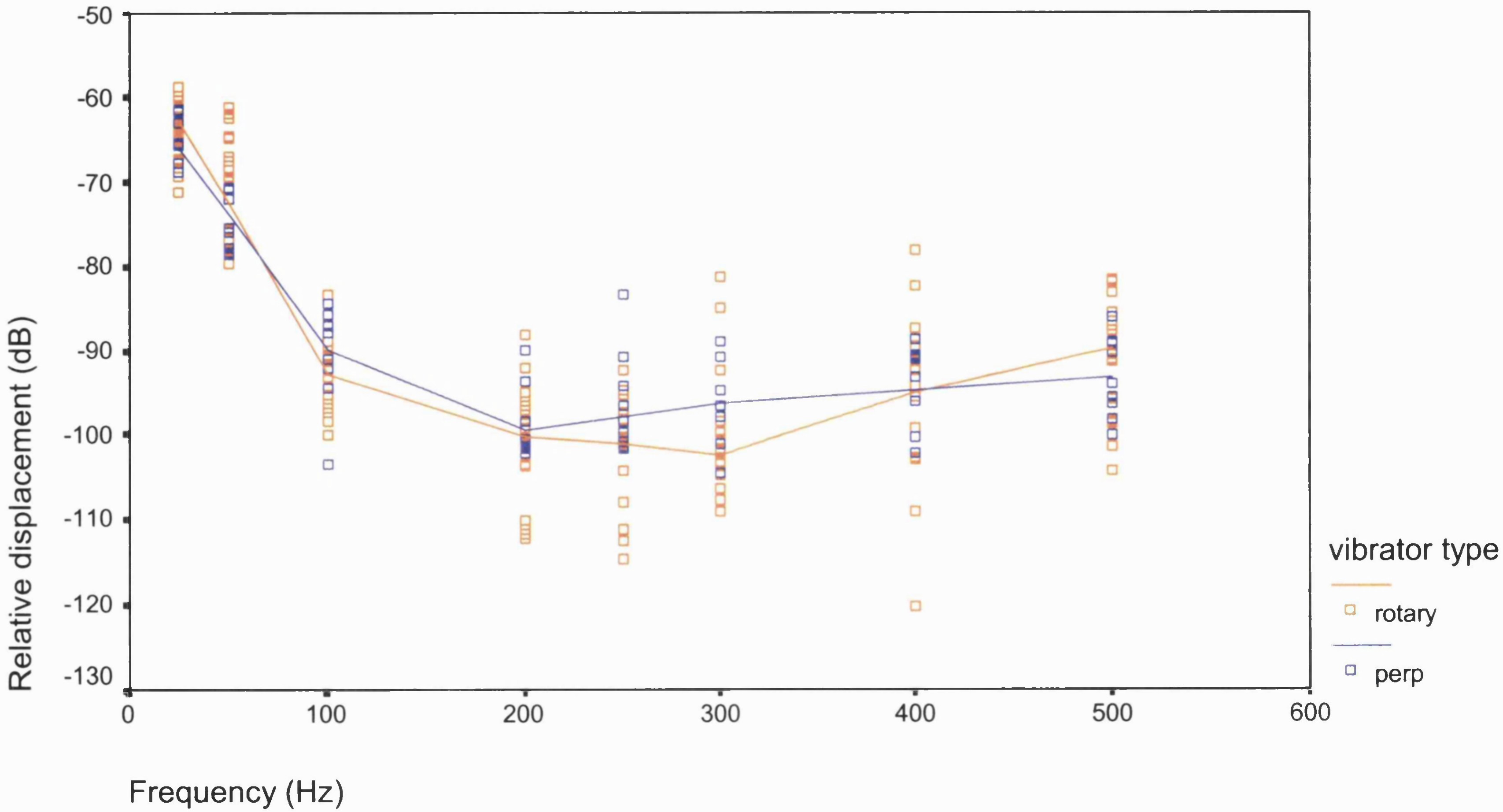


Fig 6.11: The relationship between absolute threshold from the two types of vibrator. The lines are the best fit lines (regression lines) drawn by the least squares method (LOWESS) fitting to 50% of data points. Data are from all three subjects with those from the perpendicular vibrator shifted down by 59.4dB (the mean difference between the curves) to facilitate the comparison.

6.4.3 Subjective equality (stage 2)

During this stage, the perceived level of the perpendicular vibrator is subjectively equated to the perceived level of the rotary vibrator, for a level of the rotary vibrator 10dB above absolute threshold found during the previous stage (10dB SL). The main aim of this process is to provide subjectively equated intensity levels for the two types of vibrators for the next stage (interaction test). This data also provides the possibility of investigating the intra and inter-subject relationship of the two types of vibrators. These tests are performed for all subjects at the sites originally planned (*i.e.* the middle finger for the rotary vibrator and the index finger for the perpendicular vibrator).

Figures 6.12 to 6.14 summarises the data from each subject (details in Appendix 6, Tables 1, 3 and 4).

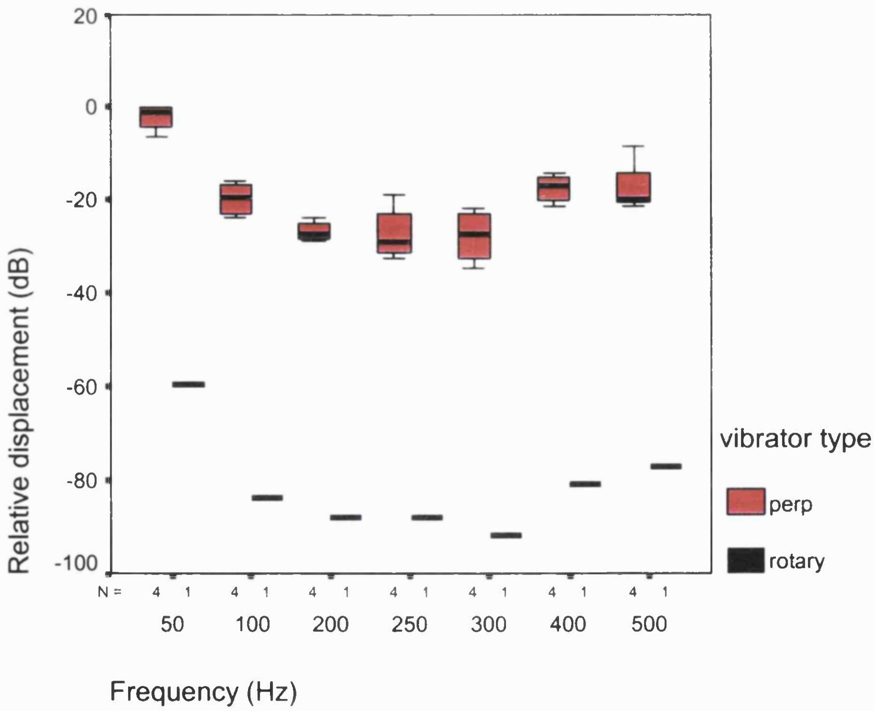


Fig 6.12: Boxplots of four runs by subject "A", showing the level of perpendicular vibration needed to match the perceived level of rotary vibration at 10dB SL (upper boxes). The lower lines are the voltage levels used to drive the rotary vibrator at 10dB SL. The small numbers on the x-axis indicate the number of observations. The smaller numbers at low frequencies are caused by the subject's response being out of the dynamic range of the device.

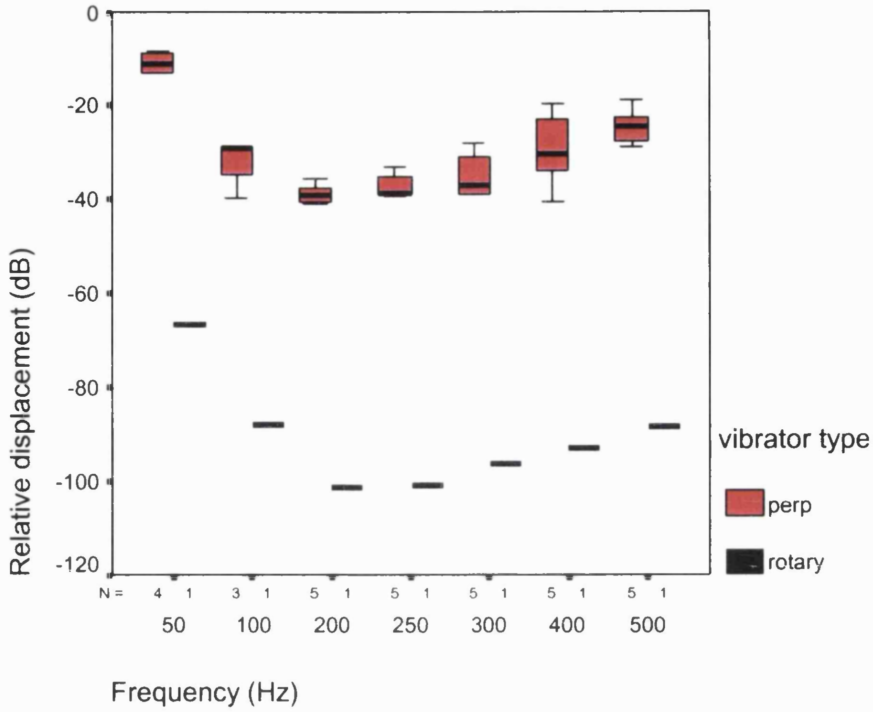


Fig 6.13: As for the previous graph but for five runs by subject "B".

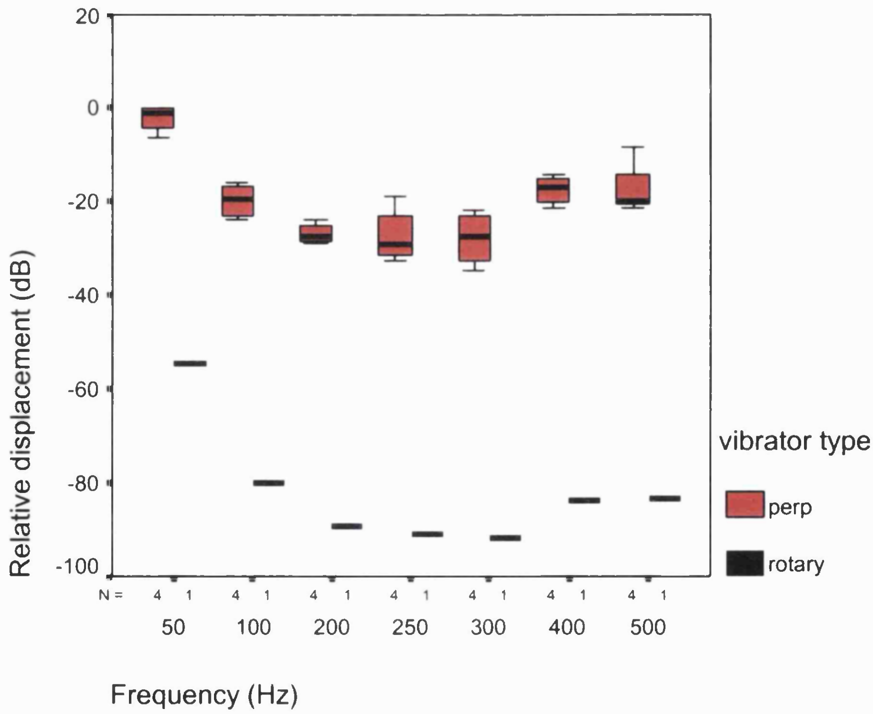


Fig 6.14: As for the previous graph but for four runs by subject "C".

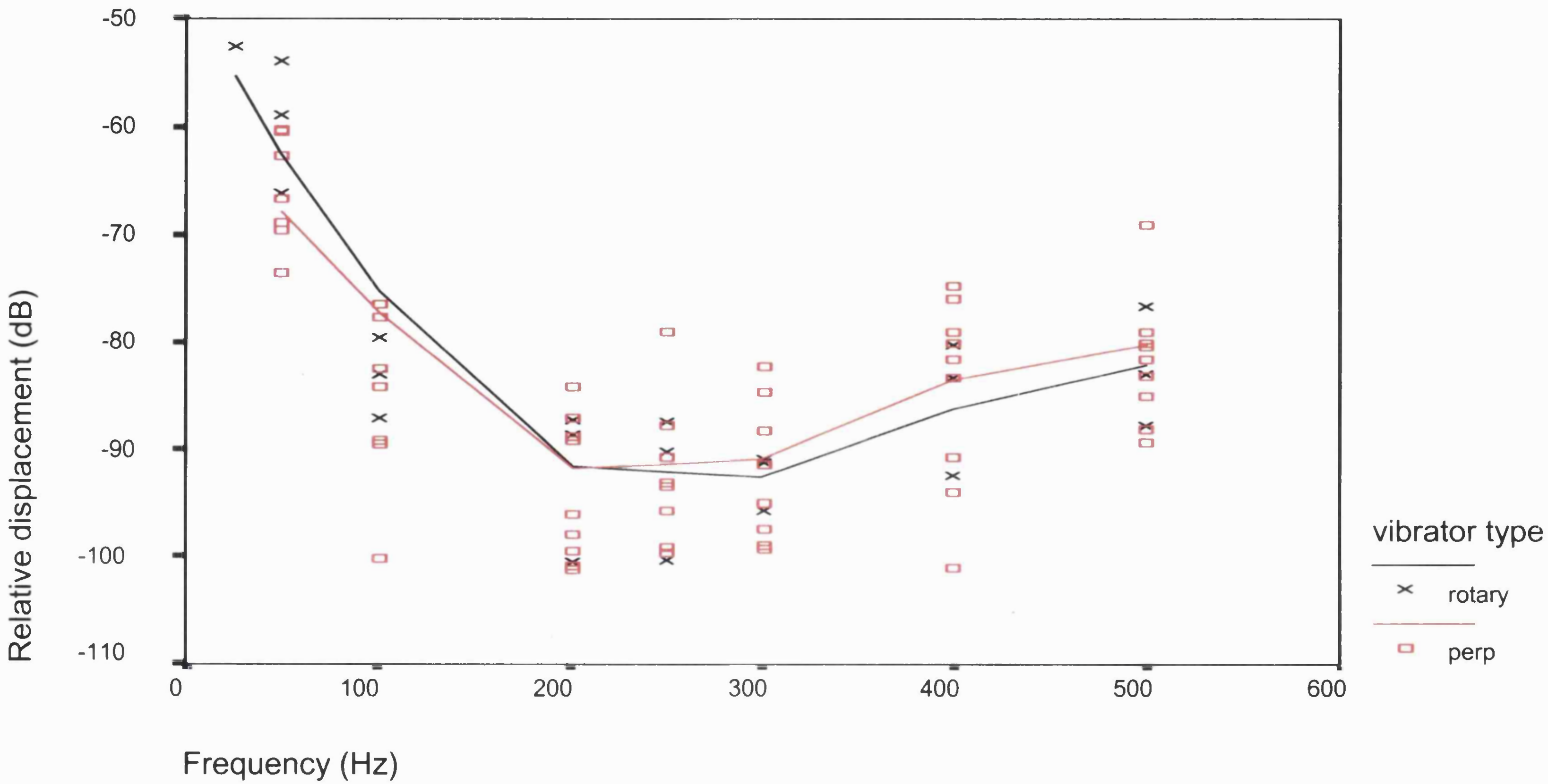


Fig 6.15: Comparison between the level of the rotary vibrator at 10dBSL and the subjectively equated level of the perpendicular vibrator. Data from the perpendicular vibrator are shifted down by 59.4dB to simplify the comparison. Data points are all the data from all subjects, with the best-fit lines drawn by the LOWESS method.

Similar to the previous stage, to facilitate the visual comparison of data, all data are presented in graph 6.15 with the average difference between the two data sets removed (process described under Section 6.4.2).

In the first instance, an ANOVA was run on the differences between the level of the adjusted perpendicular vibrator and the level of the fixed standard rotary vibrator. Subject was treated as a random factor, and frequency as a fixed factor. There was no effect of subject in either the interaction term or the main effect. Frequency as a main effect was significant ($F\ (6, 12.09)=4.82$, $p=0.012$). This means, while at threshold level the shape of the curves was dependent upon subject (results from the stage 1), at 10dB SL subject did not appear to matter. A *post hoc* analysis using Tukey's HSD test showed that the levels at frequencies of 50 and 100Hz did not differ significantly from one another, nor did those at frequencies from 100 to 500Hz (Table 6.1). The results at 100Hz were statistically equal to all other frequencies.

Table 6.1: *Post Hoc* analysis using Tukey's HSD test.

	N	Subset	
Frequency (Hz)		1	2
50	12	55.26	
100	11	60.35	60.35
200	13		62.00
250	13		62.90
300	13		63.02
500	13		63.43
400	13		64.52
Sig.		0.11	0.29

Similar to the *post hoc* test, the difference in the effect of frequency over 100Hz and under 100Hz is evident in Figure 6.16 plotted from the difference of standard and compared stimuli.

Despite the conclusiveness of evidence in indicating the difference in perceived strength from the two types of vibrator at the two regions of the curve (below and above 100Hz), these tests are unable to resolve in which section the difference lies. Recall that a similar problem was encountered during the previous stage and for two reasons the question remained unanswered. During this stage, the fixed level of rotary vibrator (*i.e.* standard stimulus), reduced the overall variations in data and hence provided better representation of samples, yet, the problem of the unknown real OVD remains unsolved.

This is where reports from the subjects become helpful (see Section 6.2.1). Most written comments returned by subjects had unusual remarks for performances at frequencies of 25 and 50Hz. The comments, in general, suggest difficulty in the comparison task. Could a difference between the sensations from the two types of vibrator contribute to the observed difference at frequencies lower than 100Hz? All subjects agreed in stating that the sensation was different at low frequencies. Note that this consistency in subjective report occurred despite the random order of frequencies presented.

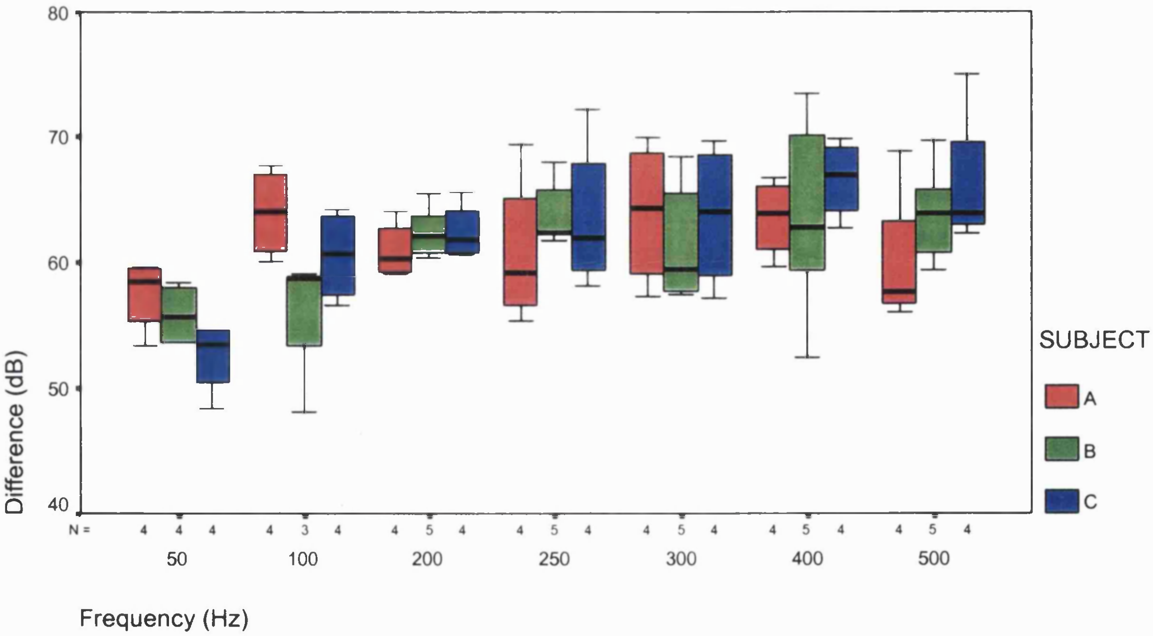


Fig 6.16: Boxplots showing the difference between the standard (rotary 10dB SL) and equated (perpendicular vibrator) stimuli across the frequency range. Data from all three subjects.

To summarise the results of this stage,

- There is no significant difference between the general shape of the 10dB SL curve from the rotary vibrator and subjectively equated perpendicular vibrator over the frequency range of 100-500Hz.
- The sensation from the rotary vibrator is significantly different from the perpendicular vibrator at 50Hz (at least - see discussion of this chapter).

Medians of the subjectively equated data from this stage will be carried forward to the next stage for the interaction test.

6.4.4 Interaction test (stage 3)

This stage is the principle aim of the project (see Section 6.2.4). It is important since it brings together effort on the preparation of equipment and subjects' contributions to assess the practicability of the introduced method for measuring interaction and the multi-channel performance of the rotary vibrator. The aim is to quantify and compare the level of interaction between two rotary vibrators with the level of interaction taking place between two perpendicular vibrators. Ideally, a further test would have been conducted to quantify the level of interaction between two dissimilar vibrators. However, due to time constraints, this was not possible.

During this stage, subject "C" could only attend two initial training sessions. Hence, the rest of this section will only describe the results from the remaining two subjects.

In relation to disappearance of subject "C" is reappearance of data at 25Hz at this stage. The reason for this goes back to the way subjects responded during the previous stage. Subject "C" had no value returned at 25Hz *i.e.* the intensity levels that this subject demanded for the perpendicular vibrator to match the 10dB SL rotary was beyond the dynamic range of the perpendicular vibrator. Subject "A" occasionally returned values and only subject "B" did return values at this frequency at all occasions. Therefore, data at 25Hz were excluded from analysis of stage 2, to prevent a biased comparison. Data at 25Hz will be used in this stage, since subject "C" (with no responses) is absent. Also, unavailability of subjectively equated values at some observations at 25Hz from subject "A" (*i.e.* its true value could have been higher) would only benefit the expected performance from the perpendicular vibrator (assuming interaction is intensity dependent).

In the interpretation of figures resulting from this stage, one point should be kept in mind. Chance performance (8 correct responses) indicates a lack of interaction between the two vibrators. Higher scores indicate greater interaction and perhaps lower performance of such vibrators in a multi-channel configuration.

Figures 6.17 and 6.18 summarise data from subjects "A" and "B". Subject "A" performed a total of three complete sets of tests (*i.e.* 48 trials) at each frequency for each type of vibrator, while subject "B" performed three complete sets of tests for the perpendicular vibrator and four for the rotary vibrator (see Appendix 7).

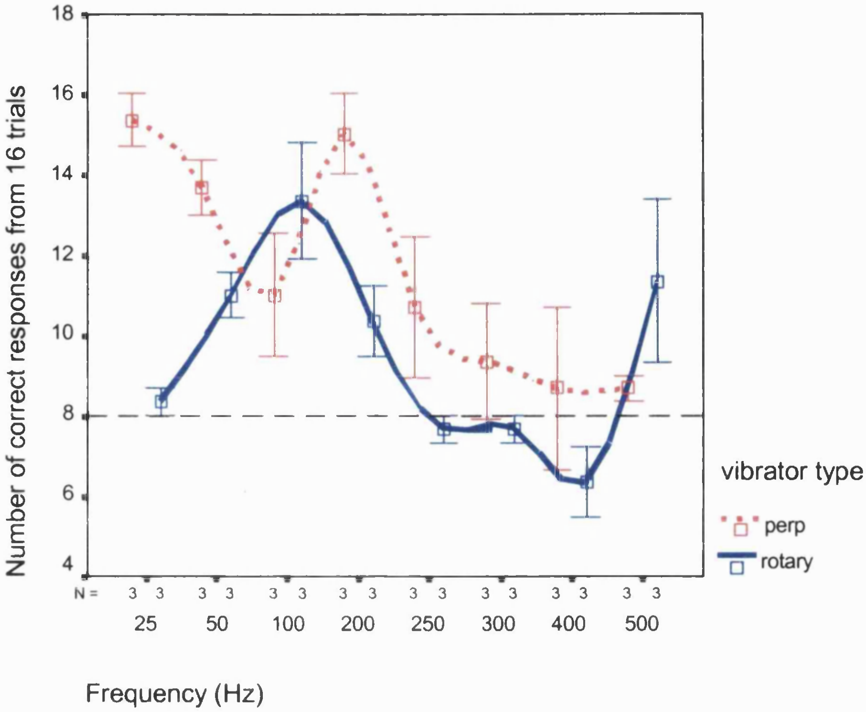


Fig 6.17: Data from the interaction test by subject "A". The horizontal dashed line shows chance performance and error bars show ±1 SE

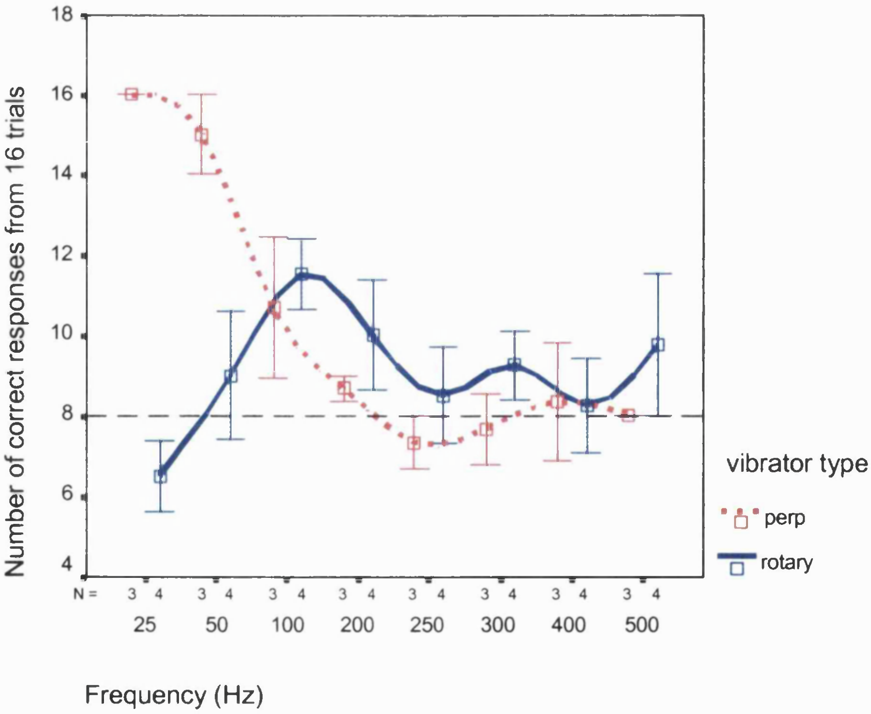


Fig 6.18: Similar to previous graph but for subject "B".

To compare performance for the rotary vibrator to that for the perpendicular vibrator a Pearson chi-square test was performed on the data from each subject. The result of the test, performed in 2 by 2 contingency table form (response × the type of vibrator), is tabulated in Table 6.2.

Table 6.2: Showing χ^2 significance (p) value between the data from two types of vibrator.

Freq. (Hz)	Subject "A"	Subject "B"
25	<0.0001	<0.0001
50	0.052	<0.0001
100	0.094	0.553
200	<0.0001	0.375
250	0.063	0.445
300	0.306	0.299
400	0.152	0.056
500	0.092	0.248

Here, a significant outcome means that the two vibrator types differ in their degree of interaction at that particular frequency. The level of significance was very high for both subjects at 25Hz. At 50Hz, while subject "B" showed very high significance, the result of subject "A" was nearly so. The results of these two subjects did not agree at 200Hz.

Attempts were made to explain the observed differences between the two types of vibrator found in the interaction test. One explanation is to assume that waves generated by each type of vibrator are damped to different extents as they spread across the skin. At low frequencies, where the receptors have a relatively small receptive field (see Chapter 3), the perception of interacting waves would be highly dependent on the extent to which its individual constituent waves could travel. For high frequencies, however, the larger receptive fields may override the differences in damping. In this way, differences in interaction may only be found at low frequencies rather than high. It may also be that the rotary vibrator by its nature stimulates the skin more locally compared to the perpendicular vibrator. This will result in a situation similar to the one described above, with differences in perceived interaction restricted to the low frequencies. Further experiments will be required to clarify this issue.

To explain the between subject differences, the comments returned by subjects once more gave a remarkable assistance. Subject "B" repeatedly commented that stimuli at a frequency of 200Hz were weak. This was despite all frequencies being presented at 10dB SL. Perceiving a weak signal for both vibrators suggests that factors such as a change in threshold (due to uncontrolled parameters- see Section 6.2.1.) may be responsible.

6.5 Conclusion

There are number of reasons why caution is necessary before making general conclusions from these results. For one thing, the interaction is expected to be an intensity dependent factor and there was no control over important parameters (such as temperature) which will affect the perceived strength of stimuli. Secondly, the number of subjects and tests were quite limited - more extensive experimentation is definitely required to eliminate the effect of uncontrolled variables. After all, these experiments were conducted with the main aim of testing the functionality of the introduced concept in measuring interaction.

By considering the above points, the following conclusions appear reasonable:

- Interaction does indeed takes place between the vibrators of similar type working in proximity of each other.
- The introduced method is a practical way to measure this interaction.
- The level of interaction between similar vibrators is highly likely to be dependent on the type of vibrator (at least) at frequency of 25Hz, with less interaction for the rotary vibrator.

Thus, this method of measuring interaction shows a clear promise in quantifying how much of the total interaction is due to mechanical interaction of waves. Unfortunately, no time was available to explore this avenue further.

6.6 Discussion

The work on the perpendicular vibrator was initiated to make a piezo replacement for the magnetic actuators currently in the market with a main aim of reducing the size and improving the displacement range. The particular design implemented here addressed these issues (see Section 5.2). However, it is important to note that the configuration adapted for the benders in the design of the perpendicular vibrator is not suitable for applications demanding a dense matrix of vibrators, since the long structure of the piezo bender, which is important to increase the displacement amplitude, limits the position of the next actuator.

Data from the pilot study (Section 6.4.1) suggested that clues regarding the presence of the stimuli were available despite the high level of masking noise and other precautions. It was speculated that travelling waves from the vibrator could have reached the subject through the supporting surface. A solution to prevent the spread of these waves could have been to damp the vibration with the use of padding under the vibrator. This method has been used by other researchers (*e.g.* Sanders, 1973; Tan, 1996). However this was avoided here, on the basis of the belief that the way reaction forces from the vibrator were dealt with could affect its action force.

On the issue of the interface between vibrator and other surfaces, it is relevant to point out that the skin obeys the vibration from the vibrator when these two surfaces are fixed to each other (*e.g.* by use of glue). Although fixing the vibrator to the skin could assure that the generated wave has been actually applied to the skin, the use of such methods was avoided since it did not simulate the conditions in which a vibrotactile device would be used.

Following experiments on the equality of sensation for the middle and index finger (pilot study), it was concluded that for the purpose of this study these two fingers will be considered equal. However, for the observed insignificant differences to be accounted for, both vibrators could have been tested on both fingers for all three stages.

In the present study, the effect of "indentation" and its related factor "applied load" were reduced by giving the subject the liberty of controlling the load. This was employed on the basis of observation, leading to the assumption that subjects will adjust the load to achieve maximum sensitivity. The matter is discussed under "common procedures" (Section 6.2.1) where subjects were requested to pause and remove their finger from the vibrators between each trial. For further studies, it might be appropriate to consider methods that are more accurate. If the controlled indentation is used to control its correlated factor load, care must be taken with regard to the viscoelasticity of skin. The viscous property of skin emphasises that by keeping the indentation constant the load will vary with time. A solution to overcome the time dependency might be to start the measurements after sufficient time was given to allow for the "creeping" period of the viscous medium to reach its maximum displacement *i.e.* steady state value. This solution might solve the time dependency but bring in the question of whether the neural receptors within the skin will still be in their optimum position. In short, the method used here appears to be a suitable alternative in case such complications could not be readily solved

CHAPTER 7

CONCLUSIONS AND FURTHER WORK

7.1 Summary

This study was begun with the long-term aim of developing a better performing vibrotactile device for deaf-blind people. A review of earlier work highlighted some of the problems and opportunities for further advances in this field. Many previous studies of advanced designs of vibrotactile aids have failed to show performance advantages over older simple designs. Primarily the issue seems to be the (surprising) failure of multichannel devices to demonstrate a greater information rate than single channel devices. On the other hand, natural methods of touch communication, such as Braille and Tadoma, seem capable of transferring sufficient information for linguistic communication at near normal rates.

Thus we concluded the main problems were related to how the touch sense was exploited and how information is encoded by the aid. This work predominantly explores the first issue, particularly with regard to multichannel devices

We started the work by emphasising the need to understand both the human sensory system (in relation to vibration) and the operation of tactile devices if any improvements were expected to be made. We treated the combination of the two as a single "system". To understand the behaviour of this system, we considered two approaches: 1) to understand the characteristics of the components which comprise the system; 2) to apply a standard input to the system as a whole and observe the output.

An analysis of the components of tactile prostheses was given in Section 2.2, while physiological and neuroanatomical studies were called on to characterise the components of human tactile sensation.

Psychophysical studies provided the basis for understanding the overall response of the system (Section 3.2). Studies were reviewed in which either the wave shape of the stimulus or the place of application of the stimulus was varied. Changes in the wave shape and the static force as well as frequency and intensity were considered as variations in the signal shape, while changes in parameters such as body location, size of the vibrator and rigid surround were considered as variation in the location of stimuli.

While these discussions resolved some questions, they raise new ones. For instance, how does the threshold change when the contactor shape is replaced with one with a similar shape but making contact with the skin only at its perimeter? Verrillo's findings (1963) established that the area of the contactor is the determining factor for the threshold and not the shape of the vibrator. In situations in which the contact area has been reduced by removing sections from the central part of its area (*e.g.* by creating numerous holes), the question of how the area should be reported needs to be considered. As a consequence, all reported contact areas were converted back from areas to diameters (a reporting method that has gone out of use), also specifying the shape of the contact.

Also, the reviewed work suggests that interactions between two tactile stimuli are not confined to a synaptic level on the nerve path in which the neural responses travel to reach cortical areas. In fact, these interactions take place at all intervening levels between the tactile receptors and cortical areas (e.g. by the regrouping of nerves and interconnecting nerves – see Section 3.3.1) and are present regardless of the distance between the two vibrators. More importantly, these complex interactions are neither a defect of the system nor the noise within a signal. In fact, they are essential for this sense to function.

As a result, the focus of the project was narrowed from developing another vibrotactile prosthesis to answering the question of why existing devices are not functioning as well as expected. We presumed that as well as the proven interaction at various levels within the complicated structure of the human system, there was also the possibility of mechanical interaction between the waves generated by multiple stimulators working in close distance. Two main reasons for this belief were evidence of travelling waves reported by other researchers, and the possibility of occurrence of mechanical interaction between waves according to basic physical principles. Consequently, the project concentrated on measuring the mechanical interaction between waves and seeking ways of reducing this interaction.

We proposed to measure the interaction using a basic physical phenomenon known as "beats". We built devices and software to see whether this concept was practicable.

To study how the interaction occurs and how it might be reduced, we developed a pair of conventional perpendicular vibrators as well as a pair of novel rotary vibrators. The hope was that the different style of vibration would lead to quantifiable differences in mechanical interaction. The rotary vibrators were used to investigate the change in perceived interaction due to different wave patterns.

The availability of various perpendicular vibrators on the one hand and the novelty of the rotary vibrator on the other, set different priorities for the design of each device. The major consideration for the design of the perpendicular vibrator was the power efficiency, while the major consideration for the rotary vibrator was the delivered power. Consequently, the design of the perpendicular vibrator was based on the piezo actuator, and that of the rotary vibrator was based on an electromagnetic actuator (voice-coil).

Calibration was considered a crucial step and performed at various levels, from the individual devices to the entire test assembly. It was realised that despite the success of the approaches taken in achieving their set objectives (see Chapter 5), the difference between the two vibrator types caused difficulty in their calibration. This difficulty was mainly due to the fact that the piezo and magnetic actuators are different in their responses across frequency.

The correctness of the calibrations was checked by performing two tests, namely a "simulated" and a "pilot" test. These calibrations concentrated mainly on issues critical for comparative studies. In effect, we did not attempt to calibrate the system with respect to standard units, in order to accelerate the process.

Experimental work involving subjects was concentrated on measuring interaction between a pair of similar types of vibrator (*i.e.* both rotary or both perpendicular). A further test would have been conducted to quantify the level of interaction between two dissimilar vibrators. However, due to time constraints, this was not possible.

7.2 Conclusions

This thesis concentrates on the possible role of wave interactions in causing the limited performance in multichannel vibrotactile devices and presents the following major outcomes:

- It uses a novel rotary vibrator for vibrotactile stimulation.

- It introduces a new method- based on detection of "beats"- to quantify the interaction between multiple vibrotactile stimulation sites and provides evidence that the method can actually measure the interaction.

- It presents evidence that the amount of interaction is highly likely to vary according to the type of the applied vibrational motion.

The third point was taken as evidence of the mechanical interaction of waves in the situation of interest here. The logical explanation for this was that two pairs of vibrating points with the points of each pair separated by a similar distance and causing the same perceived strength of vibration (subjectively equated) should produce a similar perceived interaction unless a factor prior to nerve end stimulation is involved. The only known factor at this level is the "mechanical interaction between waves". This is considered an important finding as it offers a new way to think about the design of future vibrotactile devices.

In addition, this thesis contributed to vibrotactile communication in the following ways:

- It has brought together, in one text, a comprehensive review from the fields of psychophysics, neuroanatomy, physiology and mechanical studies to provide an overall picture of vibrotactile sensation.

- It has presented a new classification of multi-channel vibrotactile devices based on the similarity of the information presented to the vibrators.

- It has suggested a new explanation for the observed similarity between the results of experiments in which the shape of the applied mechanical stimulus has changed and of those in which the initial gap between the vibrator and the skin has changed.

- It has demonstrated parallels between the masking and summation experiments.

- It has provided new data regarding the shape of the detection threshold curve of the human to the rotary stimulation.

7.3 Further work

An obvious next step for this project is to find the extent of interaction from two dissimilar vibrators working in close proximity *i.e.* would waves from different vibrators propagating in different planes interact less? If the existing equipment were to be utilised in future work, the results could readily be compared with available data (Section 6.4.4.). On the other hand, if redesign were to be considered, the following points could be taken into consideration:

The interaction test used during these experiments was performed at a set level above threshold. Since interaction may be dependent on intensity, the task could be modified to allow the intensity level of the two vibrators to be adjusted according to feedback from subject.

Similar actuators should be used in the design of the vibrators to be used in tests (at least where the intended application is for a comparative study). The difference between the electrical characteristics of the perpendicular and rotary vibrators used in this study demanded a different level of voltage for their driving circuitry, since the lowest sensitivity of one vibrator fell into the highest sensitivity of the other. The use of similar type of actuator (*i.e.* electromagnetic or piezoelectric) will make their frequency responses more similar and ease calibration.

The reliability of psychophysical testing could be enhanced by better control of temperature, use of feedback to generate displacement independent on load, employing a smaller step size when changing the intensity and by reducing the tolerance in the manufacturing of the vibrator.

Temperature is an issue that appears to need rather careful consideration. The review of Chapter 3 suggests that changes in temperature affect the threshold of tactile sensitivity at different levels, which extends from receptor to conduction of stimuli in nerves. On the other hand during experiments it appears that temperature was controlled either locally or at the larger areas *i.e.* regionally. When the temperature is locally controlled, it is expected that only the temperature of the more superficial layers of skin is altered and temperatures of deeper layers are restored by circulating body fluids (*e.g.* the blood). An example of regional temperature control is the work of Green (1977), in which the temperature was controlled by immersing the entire subject's forearm and hand in a water bath. Experiments of Lamoré and Keemink (1988), Bolanowski *et al.* (1988) and Goble and Hollins (1993) in which the temperature was controlled by heat radiated from a lamp, by locally circulated water through hollow chambers in the apparatus, and by surgical drops may considered as a local control of temperature.

The consistency of recorded thresholds may be improved with the use of a feedback in control system to produce a displacement independent of the load. Although care needs to be taken to choose an appropriate time-constant (reaction time) for the feedback process. Recall that, in the present study, the problem of displacement being dependent on load was partly overcome by both forming the inverse filter (*i.e.* adding the filter of appropriate frequency response so that the overall frequency response of the system is flat) from the measured response of the vibrators while loaded by a finger, and control of the load by the subject to achieve maximum sensitivity.

A factor that could have further contributed to the variation in recorded threshold is the value of the minimum step size selected during the tracking procedure (2dB). Although, uncontrolled temperature and initial force during these experiments were in part responsible for variation in recorded thresholds, this variation was noticed even when observations were performed very close in time. The value used during experiment here *i.e.* 2dB was estimated based on the DLI reported by other researchers (see Section

3.2). Values from other reports show the variation to be as low as 0.5dB (see Verrillo and Gescheider, 1975). Reducing this value may improve the results.

An improvement in the manufacturing tolerance of the vibrator mechanisms would be advantageous for both vibrators, yet most necessary for the rotary vibrator. In rotary movement any offset of the axis from the centre generates forces in addition to the intended torsional force.

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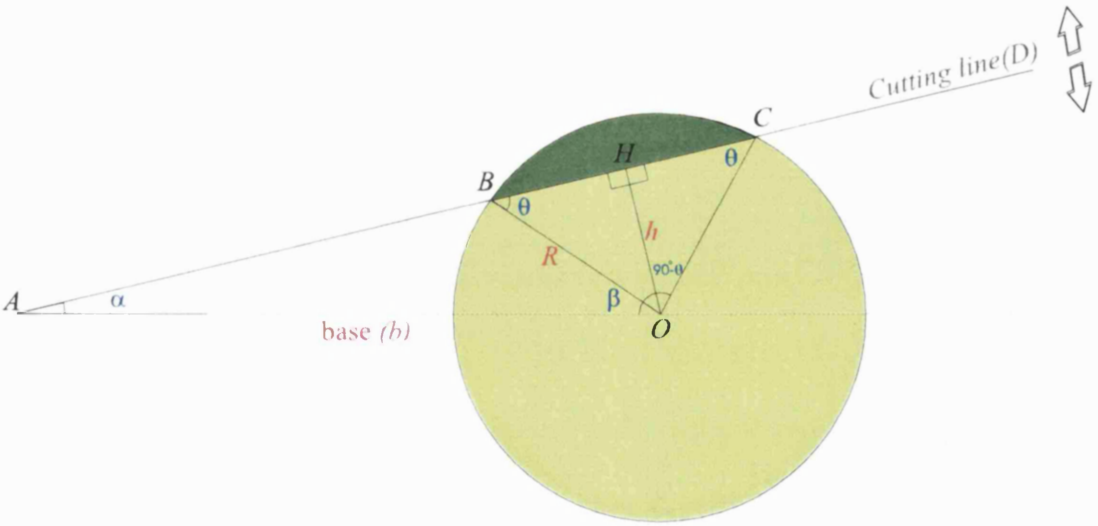
APPENDICES

APPENDIX 1

Calculation regarding the calibration of the PMD

Consider line (D) cutting a circle with the radius (R) and the centre (O) at points (B) and (C) as such to make an angle α with the line (b), which passes through the centre of the circle (O). Area of the section of the circle under the line (D) – light-green area- can be calculated as a function of α as follows:



$$\left.\begin{array}{l}\dfrac{OH}{OB}=\sin\theta=\dfrac{h}{R}\rightarrow h=R.\sin\theta\\ \dfrac{OH}{AO}=\sin\alpha=\dfrac{h}{b}\rightarrow h=b.\sin\alpha\end{array}\right\}\Rightarrow b\sin\alpha=R\sin\theta\rightarrow\sin\theta=\frac{b}{R}\sin\alpha \qquad [1]$$

$$\rightarrow\theta=arc\frac{b}{R}\sin\alpha$$

A = A-A

A  = A - A

A $= \frac{\pi R^2}{360} \times \left(180 - 2\theta^o\right)$

A $= h \times BH = h \times R.\cos\theta$

A $= R\sin\theta \times R\cos\theta = R^2 \sin\theta\cos\theta = \frac{R^2}{2}\sin 2\theta$

A $= -\frac{R^2}{2}\sin 2\theta + \pi R^2\left(\frac{90-\theta^o}{180}\right)$

A = A-A $= \pi R^2 + \frac{R^2}{2}\sin 2\theta - \pi R^2\left(\frac{90-\theta^o}{180}\right)$ [2]

$\sin 2\theta = 2\sin\theta\cos\theta$, Where $\rightarrow \begin{cases} \sin\theta = \frac{b}{R}\sin\alpha \rightarrow \theta = arc\frac{b}{R}\sin\alpha \\ \cos\theta = \sqrt{1-\sin^2\theta} = \frac{1}{R}\sqrt{R^2 - b^2\sin^2\alpha} \end{cases}$

Then,

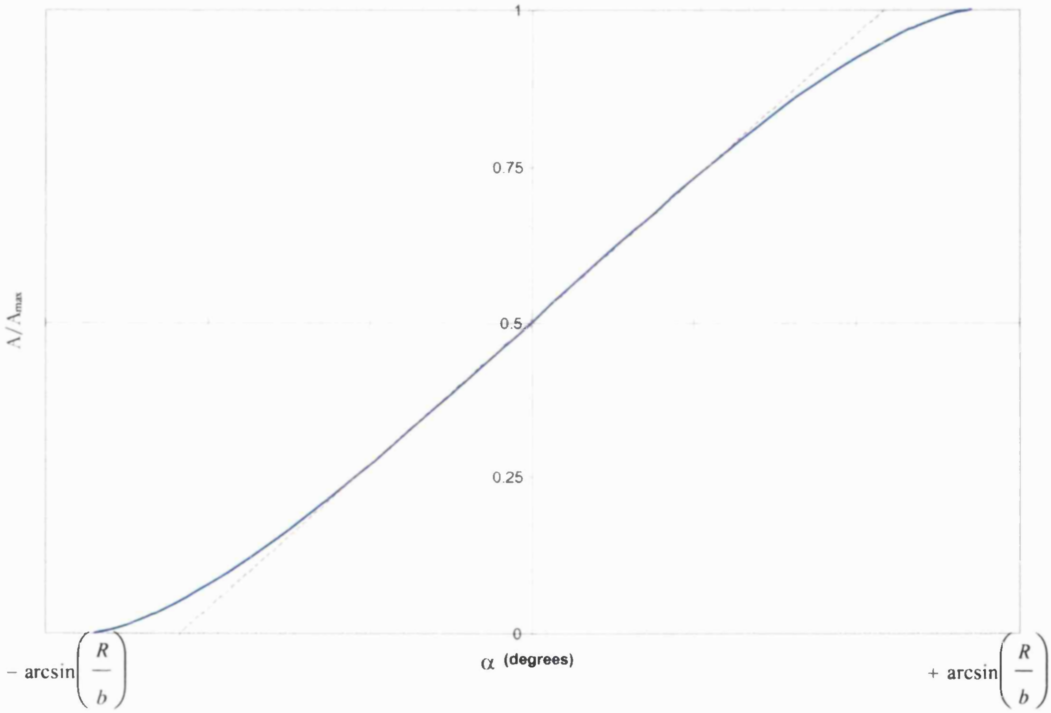
$$\sin 2\theta = 2\frac{b}{R}\sin\alpha \times \frac{1}{R}\sqrt{R^2 - b^2\sin^2\alpha}$$

$$\left.\begin{array}{l} \sin 2\theta = \frac{2b}{R^2}\sin\alpha \times \sqrt{R^2 - b^2\sin^2\alpha} \\ \theta = arc\frac{b}{R}\sin\alpha [1] \\ A_{max} = \pi R^2 \end{array}\right\} \text{Replace in equation [2]}$$

A $= A_{max} + \frac{R^2}{2} \times \frac{2b}{R^2}\sin\alpha \times \sqrt{R^2 - b^2\sin^2\alpha} - A_{max}\left(\frac{90 - arc\frac{b}{R}\sin\alpha}{180}\right)$

A  $= A_{max} + b\sin\alpha \times \sqrt{R^2 - b^2\sin^2\alpha} - A_{max}\left(\frac{90 - arc\frac{b}{R}\sin\alpha}{180}\right)$

In fact, area (A) is a function of $f(b, R, \alpha)$. Where (b) and (R) are known, the area in question depends only on the value of α, which can be seen on the following graph. The graph shows the relation between α and change in the area (A). The curve has its turning point when α= 0, corresponding to the time that line (D) passes through the centre of the circle. The curve can be approximated by a straight line for $|\alpha| < \frac{1}{2}\alpha_{max}$, where $\alpha_{max} = \arcsin\left(\frac{R}{b}\right)$, the maximum value of α which makes the "cutting line" intersect the line.



In general, the area under the line (D) reaches its extreme values at,

$$\alpha = \pm arc\frac{R}{b}\begin{cases} when, \alpha = +arc\frac{R}{b} \rightarrow Area = \max.value = \pi R^2 & (h = R) \\ when, \alpha = arc\frac{R}{b} = 0 \rightarrow Area = \frac{\pi R^2}{2} & (h = 0) \\ when, \alpha = -arc\frac{R}{b} \rightarrow Area = \min.value = 0 & (h = R) \end{cases}$$

APPENDIX 2

Data from measurements under microscope

V_{out}= Output from PMD (volt, peak to peak)
D× 20 = Measured displacement (micron)

Hz	V_{in}	V_{out}	D	V_{in}	V_{out}	D	V_{in}	V_{out}	D	V_{in}	V_{out}	D
100	4	2.8	4.5									
125	4	1.7	3.0				10	3.5	6.6			
150	4	1.1	2.0	8	1.8	3.8	10	2.3	4.6			
175	4	0.8	1.5	8	1.3	2.7	10	1.7	3.5			
200	4	0.6	1.1	8	1.1	2.2	10	1.3	2.6			
220	4	0.4	1.0	8	0.7	1.8	10	0.9	2.1			
225	4	0.6	1.0	8	1.0	1.6	10	1.2	2.1			
235	4	0.4	0.9	8	0.8	1.6	10	1.0	2.0			
240	4	0.5	0.8	8	0.7	1.5	10	1.2	1.8			
250	4	0.4	0.7	8	0.8	1.4	10	1.0	1.7			
300				8	0.4	1.0	10	0.6	1.2	10	0.62	1.2
350				8	0.4	0.7	10	0.5	1.0	10	0.52	1.0
400				8	0.3	0.6	10	0.4	0.7	10	0.39	0.7
500							10	0.2	0.6	10	0.27	0.5
560							10	0.2	0.4			
580							10	0.2	0.4			

APPENDIX 3

Technical specification of the equipment used.

The P2100 amplifier,

GENERAL SPECIFICATIONS

Power Output Per Channel: 85 watts continuous average sine wave power into 8 ohms with less than 0.05% THD, over a bandwidth of 20Hz to 20kHz, both channels driven.

Frequency Response: +0dB, -0.5dB, 20Hz to 50kHz.

Total Harmonic Distortion: Less than 0.02% at 50 watts, 8 ohms 20Hz to 20kHz.

Hum and noise: At least 110dB signal-to-noise ratio

Rise Time: 3.0 microseconds, or better (10%-90% of 1 volt at 1kHz square wave output).

Channel Separation: At least 70dB at 20kHz.

Offset Voltage: Less than ±10mV DC.

By Yamaha

SM3

GENERAL SPECIFICATIONS

Precision multi-function signal mixer

Weighting Range 0.0 to –20.0dB

Gain Accuracy 1%

Signal-to-noise ratio 110dB

Channel Separation 90dB

±10V Peak Input Signal Range

20 Ohm Output impedance 0.001% (1kHz tone ±6V) THD

0.1dB (DC to 100kHz) Spectral Variation

By Tucker Davis Technologies

TDA3-4

GENERAL SPECIFICATIONS

4 channels non-multiplexed D/A converter

Input/output level = ±10v

Conversion resolution = 16-bits, each channel

Maximum sampling rate = 500 kHz (aggregate)

S/N ratio = 87dB

THD + Noise = 85dB, 1kHz sine wave, 50kHz sampling

By Tucker Davis Technologies

AP2

GENERAL SPECIFICATIONS

Processor AT&T's DSP32C 50MHz clock

Conversion Resolution 16-bits, each channel

Input / Output Level ±10V

Signal to Noise 87dB

THD + Noise 85dB, 1kHz sinewave, 50kHz sampling rate

Maximum Sampling Rate 500kHz (aggregate)

By Tucker Davis Technologies

PA4

GENERAL SPECIFICATIONS

Precision logarithmic programmable attenuator

Attenuation range of 0.0 to 99.9dB

Attenuation resolution of 0.1dB

Attenuation accuracy of 0.05dB

Signal-to-noise ratio 110dB

±10V Peak Input Signal Range

10kOhm Input impedance

20 Ohm Output impedance 0.003% (1kHz tone ±6V) THD

0.1dB (20 to 20kHz) Spectral Variation

By Tucker Davis Technologies

PD410PI - By Sharp

TECHNICAL SPECIFICATION[♣]

High-speed silicon photodiode with integral daylight cut-off.

Length=5, Width=3.25

V_R (max)	32V
I_{sc}	3μA
Dark current (max)	10ηA
Rise/fall time	200ηs
Power dissipation	150mW
Acceptance angle	90°
Peak sensitivity	1000nm
Operating temp.	-25°C to + 85°C

SFH203 - By Kodenshi

TECHNICAL SPECIFICATION[♣]

High power GaAs IR emitter

Length=8.7, Diameter =5

V_R (max)	50V
I_{sc}	80μA
Dark current (max.)	50ηA
Power dissipation	100mW
Peak wavelength	850ηm
Rise/fall time	5ηs
Acceptance angle	40°
Operating temp.	-55°C to +100°C

[♣] The source of information is data-sheets supplied by RS electronics.

APPENDIX 4

Data from psychophysical studies - pilot investigation.

Note presented data are in the raw format *i.e.* they are values returned by the program and hence require the correction according to the frequency response of the relevant vibrator to produce the actual shape of the graph presented in Chapter 6.

Table 1: Data from the rotary vibrator- subject "A" obtained from pilot study described under Section 6.4.1. Quoted median is the median of the last six complete sets of tests (CST) where the first two CST considered as training. CSTs A to G are performed under calibration of 2.8 and are readjusted for the new calibration factor 1.6 (0dBV = 36.1dBV). Values quoted in the lower table are the standard deviation of their corresponding boxes at the upper table

Hz	A	B	C	D	E	F	G	5A12r	MEDIAN
25	-55.2	-53.2	-51.6	-52.9	-52.9	-53.6	-53.4	-47.7	-52.9
50	-55.1	-56.7	-53.4	-52.4	-52.1	-55.1	-55.4	-59.7	-54.25
100	-51.3	-69.7	-63.3	-63.6	-64	-62.3	-61.8	-62.3	-62.8
200	-51.3	-59.3	-61.3	-58.7	-56.3	-50.3	-53.7	-59	-57.5
250	-54.8	-54.8	-53.5	-55.5	-45.8	-51.5	-51.3	-54	-52.5
300	-48.1	-48.8	-43.1	-45.1	-51.8	-46.4	-44.4	-54.6	-45.75
400	-43.5	-38.2	-47.5	-49.8	-52.2	-38.2	-43.3	-40.7	-45.4
500	-40.8	-32.5	-41.8	-40.5	-38.8	-43.1	-36	-31.8	-39.65
	THESE VALUES ARE CORRECTED BY THE FACTOR OF 1.2								

Continued from the previous page

Hz	A(σ)	B(σ)	C(σ)	D(σ)	E(σ)	F(σ)	G(σ)	5a12r(σ)
25	2.7	-	1.5	1.6	1.6	2.5	2.7	2.7
50	2.1	-	1.6	1	1.5	1.9	3.3	2.4
100	1	-	1	1.6	1	2.7	4	2.2
200	2.7	-	2.4	1.9	3.6	3.3	3.5	2.4
250	2.5	-	2.3	1.5	1	4.7	1.5	1.5
300	2	-	3	2.1	2.1	1	8.5	5
400	2.5	-	5.3	1.5	2.5	2.1	2.7	3.2
500	1.6	-	1	3.9	2	1.9	1.5	3

Table 2: Data from perpendicular vibrator subject "A" obtained during the pilot study described under Section 6.4.1. Quoted medians are the medians of the last eight CST where the first two CST considered as training. CST A to H are performed under calibration factor of 2.8 and are readjusted for the new calibration factor 1.6 (0dB = 36.1dBV). Values quoted in the lower table are the standard deviation of their corresponding box at the upper table

Hz	A	B	C	D	E	F	G	H	07A11	07B11	MEDIAN
25	0.2	-6.5	-2	-0.3	0.5	-0.3	-4.8	-7.5	-1.7	-1.4	-1.55
50	-11.7	-13.1	-10.7	-13.1	-10.1	-8.4	-12.4	-14.2	-13	-17	-12.7
100	-28.1	-35.7	-25.1	-28.1	-28.4	-34.1	-27.4	-24.9	-28	-30.3	-28.05
200	-42.1	-41.8	-25.1	-27.8	-28.5	-32.8	-39.1	-39.1	-29.3	-26	-28.9
250	-42.1	-47.7	-52.1	-29.1	-30.4	-30.8	-43.1	-40.1	-14	-26	-30.6
300	-36.2	-46.8	-29.2	-30.8	-34.2	-24.2	-45.5	-40.8	-10	-22	-30
400	-42.6	-46.7	-23.3	-25	-23	-22	-37.3	-33.8	-9	-24	-23.65
500	-42.6	-45.6	-25.6	-21.6	-21	-20	-41.3	-41	-30.3	-23.7	-24.65

THESE VALUES WERE CORRECTED BY THE FACTOR OF 1.2

Hz	A (σ)	B(σ)	C(σ)	D(σ)	E(σ)	F(σ)	G(σ)	H(σ)	07A11(σ)	07B11(σ)
25	2.7	2.5	2.5	1.8	3	2	2.2	2.7	1.5	2.1
50	3.4	1.6	2.1	1.9	1.9	2.6	2.4	4.5	2.5	1.8
100	1	2.5	2.2	2.1	2.2	2.4	2.8	3.4	1.6	1.8
200	3	3	3.1	1.9	2.1	1.6	2.2	2.2	1.5	1.6
250	1.9	1.5	1	2	2.2	1.6	3.5	2.4	2.8	1.8
300	1.5	1.5	1	2	1.6	3.6	3.3	3.5	1.9	1.9
400	1.4	3.4	2.9	1.5	2.2	1.8	2.2	4.2	1	2.5
500	2.7	1.5	4.9	2.2	2.6	1	3.3	2.2	2.4	5.7

Table 3: Results from the subject "A" - perpendicular vibrator - after modifications follow the pilot investigation.

Hz	07D11	08a31	08b31	08c31	MEDIAN
25	-2.7	-9.9	-6.7	-8.7	-7.7
50	-12	-16.4	-18.9	-16.9	-16.65
100	-26.7	-31.9	-32	-28.8	-30.35
200	-30.7	-34.3	-41.5	-39	-36.65
250	-40.7	-31.6	-24.3	-35	-33.3
300	-36	-30.2	-30.2	-32.2	-31.2
400	-33	-30.8	-33.2	-32.7	-32.85
500	-33	-31.7	-28.7	-32	-31.85

Hz	07D11 (σ)	08a31 (σ)	08b31 (σ)	08c31 (σ)
25	2.2	0.5	1.1	0.7
50	1.5	2.1	1.1	0.7
100	1.5	0.7	0.8	1.8
200	2.3	2.1	1.7	1.2
250	1.8	2.5	1.2	1.6
300	1.9	1	1.6	0.9
400	1.5	1.1	1.1	2.4
500	2.4	1.3	0.9	0.8

Table 4: Comparing index (I) and middle (m) fingers subject "A". Values quoted in parenthesis following each test specify the order of presentation.

Hz	09c04/m	09a13/m	09c04/I	09a13/I	average /m	average /I
25	-49.9 (2)	-48.8 (4)	-48.3 (4)	-45.6 (2)	-49.3	-46.9
50	-50.4 (1)	-52.3 (3)	-51.3 (3)	-51.6 (1)	-51.3	-51.4
100	-65.8 (5)	-56.2 (9)	-64.2 (8)	-62.3(10)	-61	-63.2
200	-55 (6)	-48.4 (8)	-59.2 (7)	-51.5 (6)	-51.7	-55.3
250	-48.9 (10)	-33.2(14)	-50.9(12)	-40.9 (12)	-41.0	-45.9
300	-38.1 (9)	-26.8 (13)	-40.3(11)	-34.6 (11)	-32.4	-37.4
400	-38.2 (14)	-21.5 (17)	-33.7(16)	-20 (15)	-29.8	-26.8
500	-29.3 (13)	-14.3 (18)	-25.5(15)	-14.2 (16)	-21.8	-19.8

Hz	09c04/m (σ)	09a13/m (σ)	09c04/I (σ)	09a13/I (σ)
25	1.3	1.7	1.1	1
50	3.4	1.5	3.2	1.2
100	1.9	1.1	0.7	1.1
200	1.8	1.8	2.6	1.6
250	1.1	1.7	1.1	0.7
300	1.1	1.3	0.8	1.1
400	1	1.6	0.8	1.4
500	1.2	0.9	1.7	1.6

APPENDIX 5

Data from psychophysical studies - vibration threshold (Stage 1)

Note presented data are in the raw format *i.e.* they are values returned by the program and hence require the correction according to the frequency response of the relevant vibrator to produce the actual shape of the graph presented in Chapter 6.

Table 1: Medians of the rotary vibrator, index finger subject "A". After modification follow pilot investigation

Hz	7c12	7a20	08a23	08d23	08e23	MEDIAN
25	-51.3	-55.1	-50.4	-54.9	-53.3	-53.35
50	-64.3	-60.6	-57.1	-58.4	-57.8	-58.1
100	-69.7	-66.5	-63.8	-67.8	-67.7	-67.1
200	-64	-56.2	-63.5	-59.4	-52.2	-58.05
250	-52	-54.7	-54.7	-55	-56	-54.7
300	-55.3	-51.6	-56.8	-56.3	-54.8	-55.05
400	-47	-39	-41.9	-34.9	-29.9	-38.6
500	-35	-39.7	-27	-25.7	-31	-31.25

Hz	7c12 (σ)	7a20 (σ)	08a23 (σ)	08d23 (σ)	08e23 (σ)
25	1.8	2.5	1.9	0.7	1.3
50	1.5	1.6	1.3	1.8	0.9
100	2.7	1.6	1.2	2.1	2.6
200	1	1.6	1.4	1.1	0.8
250	2.5	1.6	1.6	1.1	1.4
300	2.1	1.8	1.5	0.8	1.7
400	1.9	1.5	0.7	1.1	1.1
500	2.6	1.8	1.5	0.7	0.8

Table 2: Medians of the rotary vibrator, middle finger subject "A". After modification follow pilot investigation

Hz	08c23	09c04	09c12	MEDIAN
25	-53.4	-49.9	-50.4	-50.4
50	-55.4	-50.4	-49.6	-50.4
100	-60.2	-65.8	-56.8	-60.2
200	-56.7	-55	-48.2	-55
250	-54	-48.9	-28.4	-48.9
300	-45.5	-38.1	-34.5	-38.1
400	-38.2	-38.2	-25.6	-38.2
500	-31.5	-29.3	-25.5	-29.3

Table 3: Medians of the means of five CSTs from vibration threshold test (Stage 1) - subject "B" - rotary vibrator.

Hz	07a05	07a11	07a12	07a18	07a20	MEDIAN
25	-58.3	-57.4	-61.1	-59.3	-57.1	-58.3
50	-64.1	-68.3	-65.3	-66.7	-63.9	-65.3
100	-70.2	-70.7	-71.7	-	-73.4	-71.2
200	-71.9	-72.3	-71.3	-58.3	-70.2	-71.3
250	-69.2	-64.7	-71.3	-61	-67.7	-67.7
300	-59.6	-57.7	-62.3	-53	-61	-59.6
400	-56.7	-50.3	-67.7	-39.7	-50.7	-50.7
500	-48.2	-42.3	-32.7	-25.7	-45.3	-42.3

Hz	07a05 (σ)	07a11 (σ)	07a12 (σ)	07a18 (σ)	07a20 (σ)
25	1.5	1	3.4	1.8	1.9
50	2.7	2.5	1.5	1.5	1.5
100	3.2	2.1	2.1	-	2.8
200	3.6	1.5	2.7	2.5	2.3
250	1.5	1.8	2.5	3	2.5
300	2.2	1.9	3.2	1.6	1.4
400	2.8	2.7	1.4	1.6	1
500	4.2	1.8	5.1	1.8	2.2

Table 4: Medians of the means of three CSTs from vibration threshold test (Stage 1) - subject "B" - perpendicular vibrator

Hz	06a29	07a4	07a07	MEDIAN
25	-	-8.7	-6.4	-7.55
50	-	-19.3	-19.6	-19.45
100	-44.3	-35.4	-32.9	-35.4
200	-42.8	-42.8	-41.3	-42.8
250	-42.6	-37.6	-39.3	-39.3
300	-46	-37.9	-42.4	-42.4
400	-44.3	-42.5	-38.2	-42.5
500	-40.9	-39.2	-42.8	-40.9

Hz	06a29 (σ)	07a4 (σ)	07a07 (σ)
25	-	3.5	2.7
50	-	2.4	2.2
100	3	3.2	1.6
200	3.8	3.8	3.8
250	2.2	2.2	1.9
300	2.2	2.9	2.1
400	1.5	2.4	1.5
500	5.1	2.8	2.2

Table 5: Medians of the means of four CSTs from vibration threshold test (Stage 1) - subject "C" - rotary vibrator.

Hz	08a10	08a14	08a16	08a24	MEDIAN
25	-48.7	-52.7	-53.7	-51	-51.85
50	-53.3	-51	-53	-56	-53.15
100	-64	-62.3	-63.3	-68.7	-63.65
200	-55	-57.7	-61.3	-62.4	-59.5
250	-57.3	-51.3	-58.3	-57.7	-57.5
300	-53.7	-54.7	-58	-55	-54.85
400	-37	-40	-43.7	-43.3	-41.65
500	-39.7	-35.3	-42.7	-34.3	-37.5

Hz	08a10 (σ)	08a14 (σ)	08a16 (σ)	08a24 (σ)
25	1.9	1.5	2.9	1
50	1.4	2.3	1.6	1
100	2.5	1.5	2.1	1.8
200	1.6	1.5	2.7	1.6
250	2.5	3	2.1	1.4
300	3.1	1.5	1.6	1
400	1.9	2.3	2.9	2.7
500	1.8	1.5	2.2	1.8

Table 6: Medians of the means of two CSTs from vibration threshold test (Stage 1) - subject "C" - perpendicular vibrator

Hz	o8a15	08a22	MEDIAN
25	-4	-2.3	-3.15
50	-11.7	-13	-12.35
100	-25.3	-28	-26.65
200	-42	-42.3	-42.15
250	-42.3	-41.7	-42
300	-46	-39.3	-42.65
400	-44.3	-35.3	-39.8
500	-36.7	-38.3	-37.5

Hz	o8a15 (σ)	08a22 (σ)
25	2	1.4
50	2.1	1
100	2.2	1.6
200	1	1.5
250	2.1	2.4
300	2.6	1.5
400	3.3	2.2
500	1.8	2.5

APPENDIX 6

Data from psychophysical studies - subjective equality test (stage 2)

Note presented data are in the raw format *i.e.* they are values returned by the program and hence require the correction according to the frequency response of the relevant vibrator to produce the actual shape of the graph presented in Chapter 6.

Table 1: The results of –subject "A" subjectively equated intestates for perpendicular vibrator at index finger from 10dB raised level of the measured threshold of rotary at middle finger

Hz	09a12te	09b12te	09a13te	0913bte	MEDIAN
25			3.7		3.7
50			0.3		0.3
100	20.4		21.3	18	20.4
200	31	29.6	25	22.6	27.3
250	24.3	33.6	21.6	26.6	25.45
300	23.2	23.5	22.5	25.9	23.35
400	21.2	37.5	18.2	11.5	19.7
500	20.9	21.2	20.2	20.5	20.7

Table 2: The results of –subject "A" subjectively equated intestates for perpendicular vibrator at index finger from 10dB raised level of the measured threshold of rotary at index finger

Hz	09a01te	09a05te	09a07te	09a13te	MEDIAN
25					
50	6.7	0.6	0.4	2.7	1.65
100	22.3	16.3	24	17.6	19.95
200	23.8	28.5	26.8	28.8	27.65
250	33	27.7	19	30.7	29.2
300	22.7	35.3	31.7	25	28.35
400	15.8	20.1	17.1	22.8	18.6
500	10.8	23.5	22.2	21.8	22

Table 3: The results of –subject "B" subjectively equated intestates for perpendicular vibrator at index finger to the 10dB raised level of the measured threshold of the rotary at middle finger

Hz	07A24 TE	07A26 TE	08A08 TE	09a05 TE	09A05 TE	MEDIAN
25	-1.4	-1.1	-16.3	-0.7	-2.3	-1.4
50	-8.9	-9.6	-28.6	-13.6	-13.6	-13.6
100	0	-29.4	-62.7	-40.1	-29.1	-29.4
200	-35.7	-40.8	-40.5	-37.5	-39.1	-39.1
250	-33.3	-39	-35.6	-39	-39.6	-39
300	-31.7	-37.7	-28.7	-39.7	-39.4	-37.7
400	-31.8	-24.5	-21.2	-35.2	-42.2	-31.8
500	-26.8	-24.9	-20.9	-31.2	-29.9	-26.8

Table 3: The results of –subject "C" subjectively equated intestates for perpendicular vibrator at index finger to the 10dB raised level of the measured threshold of the rotary at middle finger

Hz	09a01te	09a05te	09a07te	09a13te	MEDIAN
25					
50	-6.7	-0.6	-0.4	-2.7	-1.65
100	-22.3	-16.3	-24	-17.6	-19.95
200	-23.8	-28.5	-26.8	-28.8	-27.65
250	-33	-27.7	-19	-30.7	-29.2
300	-22.7	-35.3	-31.7	-25	-28.35
400	-15.8	-20.1	-17.1	-22.8	-18.6
500	-10.8	-23.5	-22.2	-21.8	-22

APPENDIX 7

Data from psychophysical studies - interaction test (stage 3)

Table 1: Number of correct response at 10dB SL when a pair of perpendicular vibrator s was used by subject "A".

Hz	09b21te	09c21te	09f21te	Total correct	Total wrong	MEAN	S. D.
25	14	16	16	46	2	15.3	1.2
50	15	13	13	41	7	13.7	1.2
100	14	10	9	33	15	11.0	2.6
200	13	16	16	45	3	15.0	1.7
250	14	8	10	32	16	10.7	3.1
300	9	7	12	28	20	9.3	2.5
400	9	12	5	26	22	8.7	3.5
500	9	9	8	26	22	8.7	0.6

Table 2: Number of correct response at 10dB SL when pair of rotary vibrator used by subject "A".

Hz	09a21te	09e21te	09g21te	Total correct	Total wrong	MEAN	S. D.
25	9	8	8	25	23	8.3	0.6
50	10	12	11	33	15	11.0	1.0
100	11	16	13	40	8	13.3	2.5
200	12	10	9	31	17	10.3	1.5
250	8	7	8	23	25	7.7	0.6
300	7	8	8	23	25	7.7	0.6
400	6	5	8	19	29	6.3	1.5
500	11	15	8	34	14	11.3	3.5

Table 3: Number of correct response at 10dB SL when a pair of perpendicular vibrator was used by subject "B".

Hz	08a10te	8a23te	08a31te	Total correct	Total wrong	MEAN	S. D.
25	16	16	16	48	0	16.0	0.0
50	16	13	16	45	3	15.0	1.7
100	14	10	8	32	16	10.7	3.1
200	9	8	9	26	22	8.7	0.6
250	8	6	8	22	26	7.3	1.2
300	9	6	8	23	25	7.7	1.5
400	8	11	6	25	23	8.3	2.5
500	8	8	8	24	24	8.0	0.0

Table 4: Number of correct response at 10dB SL when a pair of rotary vibrator was used by subject "B".

Hz	08a14 te	08a16 te	08a25 te	09a11 te	Total correct	Total wrong	MEAN	S. D.
25	8	8	5	5	26	38	7.0	1.7
50	11	8	12	5	36	28	10.3	2.1
100	14	11	10	11	46	18	11.7	2.1
200	14	8	9	9	40	24	10.3	3.2
250	7	12	8	7	34	30	9.0	2.6
300	9	11	10	7	37	27	10.0	1.0
400	10	8	5	10	33	31	7.7	2.5
500	8	8	15	8	39	25	10.3	4.0

APPENDIX 8