VIBROTACTILE PERCEPTION OF MUSICAL PITCH

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor of Philosophy

by

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ABSTRACT

Previous vibrotactile research has provided little or no definitive results on the discrimination and identification of important pitch aspects for musical performance such as relative and absolute pitch. In this thesis, psychophysical experiments using participants with and without hearing impairments have been carried out to determine vibrotactile detection thresholds on the fingertip and foot, as well as assess the perception of relative and absolute vibrotactile musical pitch. These experiments have investigated the possibilities and limitations of the vibrotactile mode for musical performance.

Over the range of notes between C1 (32.7Hz) and C6 (1046.5Hz), no significant difference was found between the mean vibrotactile detection thresholds in terms of displacement for the fingertip of participants with normal hearing and with severe/profound hearing impairments. These thresholds have been used to identify an optimum dynamic range in terms of frequency-weighted acceleration to safely present vibrotactile music. Assuming a practical level of stimulation ≈10dB above the mean threshold, the dynamic range was found to vary between 12 and 27dB over the three-octave range from C2 to C5. Results on the fingertip indicated that temporal cues such as the transient and continuous parts of notes are important when considering the perception of vibrotactile pitch at suprathreshold levels.

No significant difference was found between participants with normal hearing and with severe/profound hearing impairments in the discrimination of vibrotactile relative pitch from C3 to C5 using the fingertip without training. For participants with normal hearing, the mean percentage of correct responses in the post-training test was greater than 70% for intervals between four and twelve semitones using the fingertip and three to twelve semitones using the forefoot. Training improved the correct responses for larger intervals on fingertips and smaller intervals on forefeet. However, relative pitch discrimination for a single semitone was difficult, particularly with the fingertip. After training, participants with normal hearing significantly improved in the discrimination of relative pitch with the fingertip and forefoot. However, identifying relative and absolute pitch was considerably more demanding and the training sessions that were used had no significant effect.

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DECLARATION

The research in this thesis was carried out as part of the project 'Interactive performance for musicians with a hearing impairment' (No. AH/H008926/1) which was funded by the Arts and Humanities Research Council (AHRC). Professor Carl Hopkins at the University of Liverpool was the Principal Investigator and Professor Jane Ginsborg at the Royal Northern College of Music (RNCM) was the Co-Investigator. This thesis presents work that is directly attributable to the author who was supervised by Professor Carl Hopkins and Dr Gary Seiffert at Liverpool.

The experiment on detection thresholds was designed, programmed, implemented and analysed by the author at Liverpool.

The experiment on relative pitch discrimination was designed by the author in conjunction with partners at RNCM. The experiment was programmed and implemented by the author with all recruitment and testing on the foot at Liverpool but recruitment and testing on the fingertip shared with RNCM. All analysis was carried out by the author but compared with an independent analysis carried out by RNCM.

The experiment on relative and absolute pitch learning was mainly designed by RNCM along with input from the author and Professor Hopkins, but it was programmed and implemented by the author with all recruitment and testing on the foot at Liverpool; the recruitment and testing on the fingertip was carried out by RNCM. All analysis was carried out by the author, but this was compared with an independent analysis carried out by RNCM.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

1 INTRODUCTION

This chapter introduces the main research topics to give the context for the research and present the terminology. The main sections include the background and motivation for the project, the objectives and research questions for the experimental work and the thesis organisation.

1.1 BACKGROUND AND MOTIVATION

This section gives the background to this inter-disciplinary research in acoustics, vibration and music as well as its relation to both perceptual and physical processes for people with normal hearing and with hearing impairments.

1.1.1 Interactive performance for musicians with hearing impairments

The research in this thesis was carried out under the project "Interactive performance for musicians with a hearing impairment" which was funded by the Arts and Humanities Research Council. The project was instigated by Professor Carl Hopkins at the University of Liverpool who was inspired to investigate the use of vibration reported by Dame Evelyn Glennie, the world-famous percussionist who is profoundly deaf. It was hoped that one of the outcomes of the project would be to increase the possibilities for music-making by deaf musicians by focussing on interactive performance. Dame Evelyn Glennie said "People think that music means nothing to the deaf; but it is important to them whether they are interested in it or not. The satisfaction of feeling vibrations, and being able to communicate through music, gives deaf children the greatest pleasure" [1]. In the UK, there are about 820,500 people with severe or profound levels of hearing loss[1] and over 45,000 children who are deaf [2]. Contrary to what is commonly thought, there are numerous skilled musicians with a severe or profound hearing loss around the world [3].

There are potential benefits to society from this research exploring the possibilities of learning to perceive and play vibrotactile music (i.e. musical vibrations transmitted through the skin), which could help to develop new

[1] Hearing loss levels are defined in [2].

strategies and ideas for integration into mainstream education [4, 5]. The two main aims of this project were (a) to investigate the social and cognitive processes underlying interactive performance by musicians with hearing impairments, primarily undertaken by the co-researchers at the Royal Northern College of Music (RNCM) and the charity Music and the Deaf; and (b) to develop a solution using vibration signals that can facilitate interactive performance, which was primarily led by the University of Liverpool. The latter involves research into the tactile perception of music signals using vibration and the design of subjective experiments in order to explore vibrotactile perception as a substitute for hearing.

Figure 1.1 shows a prototype solution for two musicians interacting with each other using two vibrating footrests per musician. The musician on the left hand side of the figure plays the guitar sending its signal to both his own forefoot and the forefoot of the co-performer, who is playing the bass guitar and sending its signal to both his own heel and the heel of his co-performer.

Figure 1.1 Proposed solution for two musicians, each using two vibrating footrests.

The proposed solution may be extended for a larger number of musicians. Figure 1.2 shows the ideal setting where sound from the instruments is picked up by microphones and taken to a mixer. Each musician has their own computer control sent over the main mix that distributes the required signals simultaneously to individual vibrating footrests or decks.

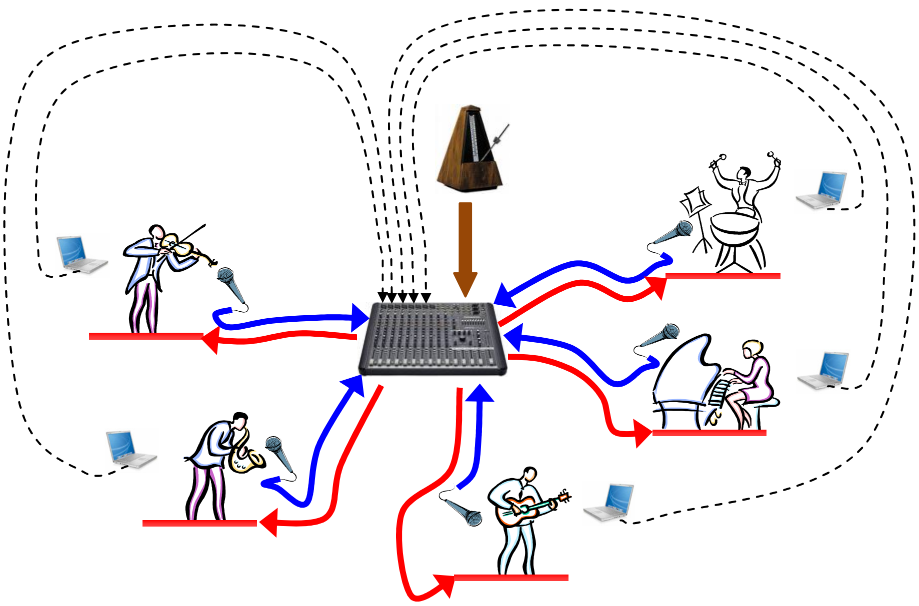

Figure 1.2 Basic concept for interactive performance for musicians with hearing impairments.

The University of Liverpool has recently published[2] a video on the internet showing proof of principle for interactive musical performance using vibration and experimental results have been presented at various conferences [6-11]. A final dissemination conference for the public was organized at the end of the project to discuss motivations, challenges and strategies for musicians with hearing impairments. Guest speaker Dr Martin Harlow (RNCM) presented Beethoven's brief life history of deafness and music. Conference participants included the professional musicians with hearing impairments pianist Danny Lane (Music and the Deaf), opera singer Janine Roebuck, piano tutor Angela Taylor and flautist Ruth Montgomery who said in a talk to trainee teachers: "Not many people out there understand how important music is to deaf children. There are many different ways it can help children to learn" [12].

[2] https://stream.liv.ac.uk/kgfymdz4

1.1.2 Psychophysics

The science of psychophysics was conceived for measuring physical stimuli and their corresponding mental events and became an intensive area of psychological research in the early 1800s [13]. In the mid 1800s, the pioneering scientists E. H. Weber and G. T. Fechner investigated the limits of human sensory capacity by creating predictive mathematical models and considering physiological functions of the sensory organs and some parts of the nervous system. This was in order to establish a quantitative relationship between the magnitude of a stimulus in the physical domain and the magnitude of a sensation in the psychological domain [14, 15]. Over the last few decades, auditory psychophysical and neural models of perception have been intensively developed in order to provide social and technological benefits [16]. Tactile models are now increasingly researched by adapting methods used in psychoacoustics, the branch of psychophysics that links acoustical stimuli with auditory sensations.

Cross-modal plasticity refers to the re-organization of the nervous system as a result of sensory deprivation, which can occur naturally or through the acquisition of new skills or training [17]. In the realm of touch, sensory substitution refers to the acquisition of environmental information through sensors for conversion into signals that can be presented to the skin using vibration transmitters [18, 19].

The glabrous (i.e. non-hairy) skin of the fingertips tends to be more sensitive to detect vibration than the hairy skin on the forearm [20, 21] and the hands are among the most sensitive parts to vibration [18]. Since the early 1960s or so, there has been an integration of psychophysical and physiological knowledge [22]. Verrillo and Bolanowski [23] used psychophysical methods to show how natural receptors and their associated nerve fibres contribute towards the perception of mechanical vibration in the glabrous skin. Vallbo and Johansson [24] studied the characteristics of these mechanoreceptors using electro-physiological methods and divided the receptors into four types which are shown in Figure 1.3.

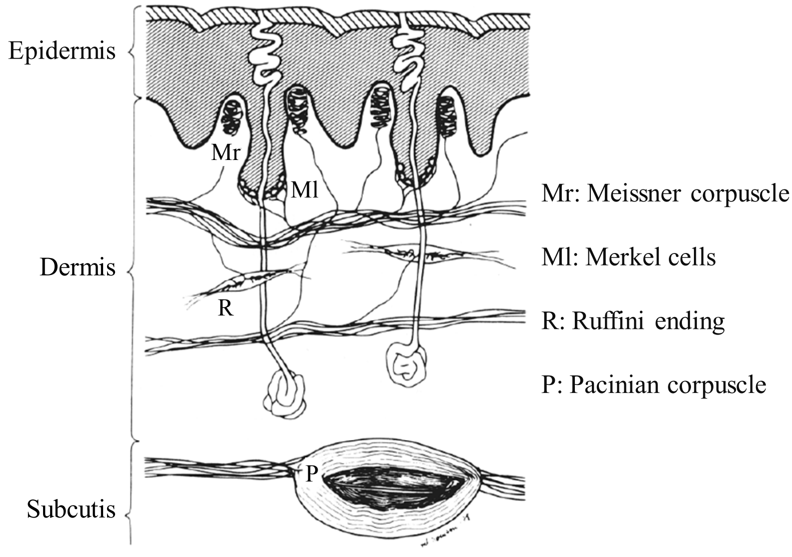

Figure 1.3 Vertical section through the glabrous skin of the human hand (reproduced from [25, 26]).

Two types of mechanoreceptors are associated with rapidly adapting (RA) nerve fibres that respond selectively to vibration and at the onset and removal of a moving object [25-29]. The Meissner corpuscle (RAI) responds between approximately 10 and 40-50Hz (and can extend up to about 100Hz [23, 30]) with high sensitivity near 20 or 30Hz [23, 31]. The Pacinian corpuscle (RAII) responds above 40 or 50Hz up to approximately 800Hz with maximum sensitivity near 250Hz [23, 31]. Two slowly adapting (SA) receptors respond to light touch throughout a sustained mechanical indentation. The Merkel cells (SAI) have a broad response to vibration below approximately 10Hz [23, 25, 32] and the Ruffini ending (SAII) is relatively insensitive and is found only in the hairy skin [23].

1.1.3 Vibrotactile speech and music

Clinical research and development of tactile aids for speech perception has been mainly motivated by the use of vibration to transmit speech for people with hearing impairments. In addition, medical imaging techniques have shown brain activity in the auditory cortex of a congenitally deaf adult indicating the ability to discriminate between two different vibration frequencies applied to the hand [33].

Originally, electro-acoustical technologies have been used as tactile aids. Flanagan *et al* [34] explains that the idea of transmitting speech telegraphically was based on the voice physiologist Bell whose vision was to make a current of electricity vary in intensity as the air varies in density when speech is produced, i.e. the notion of preservation of the acoustic waveform. According to Cholewiak and Wollowitz [35], an unpublished report by Levitt in 1985 reveals that Bell invented the telephone while working on a speech waveform display for people with hearing impairments. The first voice transmitted through the telephone was demonstrated in the Centennial exhibition of 1876 when Bell patented this invention. However, the driving force behind the commercialisation of the telephone was actually musical rather than speech transmission. The Ader telephone system made it possible to broadcast the singing on the stage and the music in the orchestra of the Grand Opera at Paris in 1881 [36].

Juang and Chen [37] describe how the invention of the Voder (i.e. Voice Demonstrator Recorder) and the Vocoder (i.e. Voice Encoder) at Bell Telephone Laboratories in the 1930s was motivated by the need to increase the communication capacity in telephone networks. The aim was to remove redundancies from the speech signal transmitted and received, which is also known as coding and involved a complex interrelationship of study topics such as phonetics, linguistics, physiology, and psychoacoustics. Around that time, the technology for telephone loudspeakers was adapted for speech training of children [38] and adults [39] with hearing impairments.

In the 1940s, there was a great deal of development to control the amplitude and frequency of the speech waveform using telephone loudspeakers until shakers became one of the most commonly vibration transmitters used in tactile research [35] due to their technical similarity and their wide frequency range.

1.1.4 Vibrotactile range of fundamental frequencies

Sinusoidal stimuli are normally used in vibrotactile research [22]. Preliminary tests in the present project indicated that only the fundamental frequencies of music notes or chords from instruments such as guitar and trumpet (see Figure 1.4) were sufficient to provide similar vibrotactile sensation of pitch on the fingertips for the same notes or chords that included additional frequency components. This is important in order to complement aspects of vibrotactile music such as rhythm and intensity. The next chapter will discuss further developments in tactile aids for speech perception and the current needs for adaptation to musical purposes.

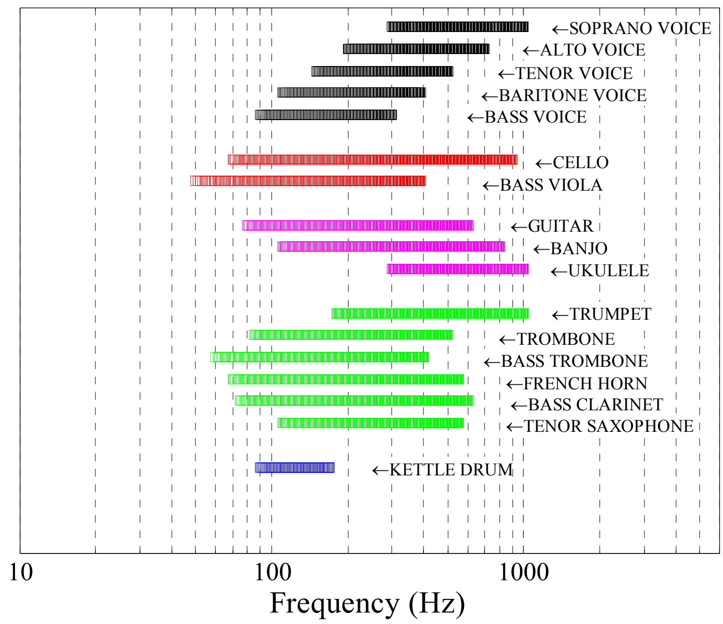

Figure 1.4 Range of fundamental frequencies for music instruments (adapted from [40]).

1.2 OBJECTIVES AND RESEARCH QUESTIONS

The objectives and research questions for each of the vibrotactile experiments carried out in this project are explained in this section. There were three main experiments: (1) detection thresholds, (2) relative pitch discrimination and (3) learning relative and absolute pitch. People with normal hearing and with hearing impairments participated in the experiments. The body locations used for the experiments were the fingertip of the middle finger, the forefoot and the heel. The experiments involved the design and implementation of bespoke vibrotactile contactor discs and graphical user interfaces that allowed the measurement of the participants' responses.

Statistical confirmation of the hypotheses for the research questions below was based on the choice between the null hypothesis to be tested and the alternative hypothesis which differs from the hypothesis being tested [41]. A hypothesis was tested based on a comparison of the mean of two samples in order to determine whether two populations were different.

1.2.1 Experiment on detection thresholds

The main objective of this experiment was to measure and establish the lowest levels (i.e. thresholds) of vibration at individual musical notes that can be felt via fingertips, forefeet and heels in order to explore the potential for vibrotactile stimuli with interactive musical performance.

An additional objective was to investigate the effect of occluding the entrance to the ear canal and the repeatability of the results when testing the fingertips.

Another objective using the fingertips was to test the ability of participants to perceive the transient parts of musical notes, i.e. the start and end of the notes, and the continuous parts between the start and the end. An overview of the experiment is shown in Figure 1.5.

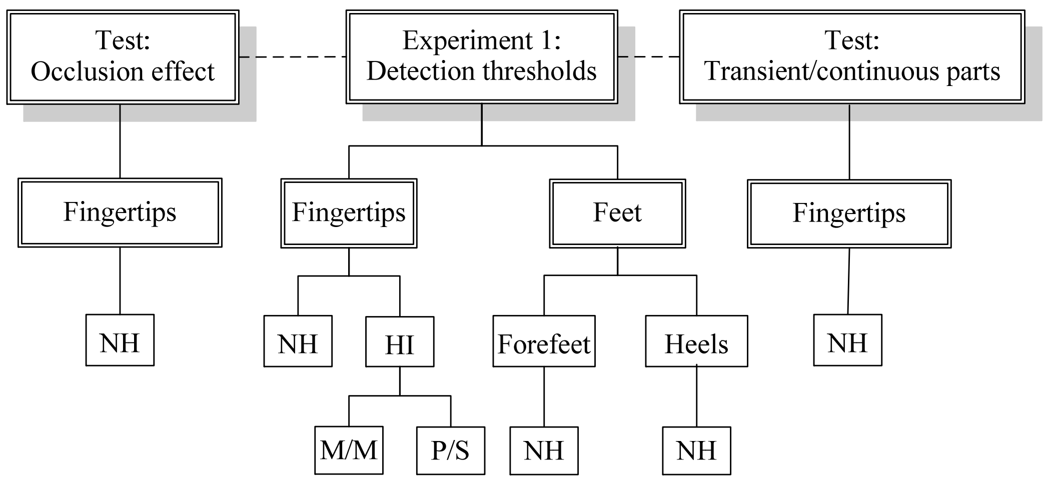

Figure 1.5 Main experiment on detection thresholds and its variations (a) to test both the occlusion effect and the repeatability of results, and (b) to detect transient and continuous parts of musical notes. Participants took part with normal hearing (NH) and with mild/moderate (M/M) and profound/severe (P/S) hearing impairments (HI).

These objectives were motivated by the following research questions:

- Does the occlusion effect influence measurements of vibrotactile detection thresholds on the fingertips?
- What are the mean detection thresholds for fingertips, forefeet and heels?
- Are the thresholds different on fingertips, forefeet and heels?

- What is the vibrotactile dynamic range that could be safely used by musicians?
- Are transient and continuous parts of musical notes both felt?

1.2.2 Experiment on relative pitch discrimination

The objective of this experiment was to investigate the perception and learning of vibrotactile relative pitch discrimination (i.e. the ability to distinguish one musical note as being higher or lower than another) via fingertips and forefeet. An overview of the experiment is shown in Figure 1.6.

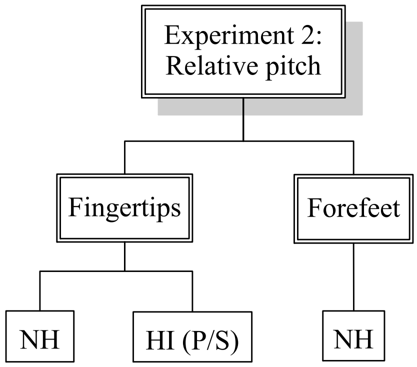

Figure 1.6 Overview shows the experiment on relative pitch discrimination. Participants had normal hearing (NH) and profound/severe (P/S) hearing impairments (HI).

The above objectives were motivated by the following research questions:

- What musical intervals can be distinguished correctly via fingertips and forefeet?
- Can this ability be improved with training?
- Does a hearing impairment affect this ability?

1.2.3 Experiment on relative and absolute pitch learning

The objective of this experiment was to investigate the perception and learning of both relative pitch and absolute pitch identification via fingertips and forefeet. For the purpose of this experiment, absolute pitch is the ability to identify a pitch tone without reference to another tone. An overview of the experiment is shown in Figure 1.7.

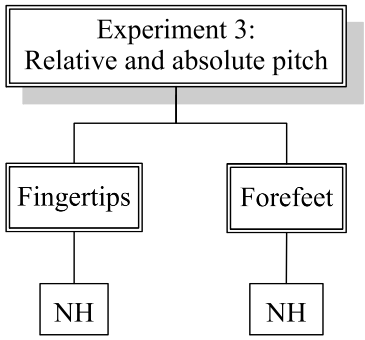

Figure 1.7 Overview shows the experiment on relative and absolute pitch learning. Participants took part with normal hearing (NH).

The above objectives were motivated by the following research questions:

- What musical notes can be identified correctly via fingertips and forefeet?
- Can the identification of relative and absolute pitch be improved with training using fingertips and forefeet?

1.3 CHAPTER LAYOUT

Chapter 2 reviews the literature on relevant vibrotactile devices along with experimental conditions and methods. Chapter 3 describes the experimental set-ups and the objective aspects of sound and vibration measurements. Chapters 4, 5 and 6 present the procedural aspects and the results from the subjective experiments.

Chapter 4 presents intensity and temporal aspects of pitch for the effective and safe presentation of vibrotactile music. These findings are based on mean detection thresholds in terms of displacement for the fingertip, the forefoot and the heel. The thresholds for participants with normal hearing are compared with those for participants with hearing impairments. In addition, the thresholds for participants with normal hearing are converted into frequency-weighted acceleration in order to establish a usable dynamic range.

Based on the results from Chapter 4, Chapter 5 describes the presentation level of stimuli that is comfortable and easy to feel and that avoids effects of high vibration intensity affecting pitch perception. This chapter defines the extent to which relative pitch can be discriminated correctly and improved through training using the fingertip or the forefoot. In addition, a comparison of this ability before the training is made between participants with normal hearing and with severe or profound hearing impairments.

Based on the results and the range of notes from Chapter 5, Chapter 6 assesses the extent to which relative and absolute pitch can be identified correctly and improved through training using the fingertip or the forefoot of participants with normal hearing. Chapter 7 concludes on the main findings in this thesis and suggests future work.

2 LITERATURE REVIEW

This chapter provides an overview of previous developments in vibrotactile aids and analyses work related to the main topics in this project, namely the detection of thresholds and the discrimination and identification of musical pitch in the vibrotactile mode. Experimental conditions that require careful consideration are discussed for the collection of valid reliable data and for further analysis and assessment of results.

2.1 INTRODUCTION

In the taxonomy of the somatic senses providing information about the state of the body, the main topics in this section fall within the realm of touch or haptics, i.e. the sensory information about objects in contact with the skin [42, 43]. The main topics deal mostly with the sense of mechanical pressure and vibration arising from the skin mechanoreceptors (see Chapter 1), and partly with the sense of temperature and potentially damaging stimuli arising from the nerve cells known as thermoreceptors and nociceptors, respectively [28].

Most of the early developments of vibrotactile aids for people with hearing loss have been focussed on speech education rather than music. Traditionally, vibrotactile cues in terms of intensity, frequency and rhythm have been important to complement learning and communication methods of speech for people with hearing loss. The need for communication is the common denominator for vibrotactile cues that also complement auditory cues for musical purposes, as discussed later in this chapter. Thus, previous research related to vibrotactile speech needs to be reviewed in the context of learning through training and the conditions that enable people with hearing loss to enjoy their communication experience also through singing or musical performance.

McEntee [44] has highlighted the major issues in deaf history and education since Aristotle the philosopher. Methods of speech training using the sense of touch can be traced back to the mid 16^{th} century. Educational methods from that time are still used nowadays and involved placing the pupil's hand on the face or throat of the teacher to allow the communication of speech features [45]. In the mid 18^{th}

century distinct approaches were established to teach children with deafness involving either oral methods such as lip reading, or sign language [46].

Plant [45] makes a cursory review of contemporary developments over the 20th century starting in the 1920s with the pioneering Teletactor which was a desktop unit used in classroom activities for voice education of children with hearing impairments [38]. However, a period of controversy and decline in the use of tactile aids started after the World War II and lasted until the late 1960s [6]. This was partly due to the accelerated development of electronics, miniaturisation and wearable hearing aids, plus the belief that there was a relatively small population of people with profound deafness. However, the hearing aids were produced with little scientific study and conveyed rather limited information to many persons with profound deafness [47]. This was expected to improve by developing new tactile aids.

Because the capacity of the human skin to transmit efficiently speech information could not be demonstrated, Kirman [48] published a review in the early 1970s advocating tactile aids and claiming that these needed to use suitable ways of coding speech to address the limitations of the skin as a communication medium. Subsequent critical reviews were published by Risberg [49] to analyse the lack of success in coding strategies and Sherrick [50] to discuss the necessity of alternative pathways to conventional hearing aids. On this basis, considerable scientific advancements were made that enabled wide commercial availability of tactile aids, especially during the 1980s.

Some examples for speech training using a single vibration transducer have exploited the conduction of sound to the inner ear through the bones of tactile aid users. Examples of this included a hand-held hearing aid driving bone conductors [51] and the Radio Ear [35], a bone conduction vibrator that has also been used as a tactile aid for lip reading. Other examples are the Minivib [45, 52] and its different versions [35, 53] and the Tactile Acoustic Monitor [45, 54] which were capable of presenting amplitude and time-varying aspects of speech. Another example was the Fonator [55] and Minifonator [53, 56] used as a sort of loudspeaker. All these examples were relatively successful in the detection and identification of environmental sounds and syllable rhythm and stress, although they were limited in phoneme identification which requires fine-structure spectral cues. The Tactilator [57, 58] was another single-channel aid based on the traditional tactiling method to monitor one's own voice.

In addition, multichannel systems included the different versions of both the Tactaid which was designed to be similar to the Tactilator [59] and the vibrotactile vocoder driving a set of single-frequency transducers [53, 60, 61], including an early version with a bone conduction vibrator attached to each fingertip of the user [49]. Another example is the Tactuator [62], a three-channel device for simultaneous stimulation of the thumb, index finger and middle finger, which used coded stimuli for their optimal discrimination with minimum training.

An unprecedented amount of research in this field has occurred since the 1990s to develop interface systems or displays of vibrotactactile information using different types of electromechanical transducers other than coil configurations (e.g. piezoelectric, miniature DC motors) and also different transduction approaches such as electro-cutaneous using different types of electro-stimulation. Some recent comprehensive reviews are provided in [18, 50, 63-69]. In addition, guidelines and future trends for the design of haptic and vibrotactile interfaces are provided in [70] and new international standards are under development to evaluate the area of tactile and haptic interaction [43, 71].

2.2 VIBROTACTILE DETECTION THRESHOLDS

Establishing psychophysical detection thresholds of vibrotactile sensitivity as a function of frequency is important in clinical research to estimate adverse effects of hand-arm vibration exposure on the sensory system [32]. In the present study, the detection thresholds are established to answer the research questions from Chapter 1, in particular to assess later suprathreshold levels within a dynamic range that can be safely used with specific contact areas for the fingertip and the forefoot. The experimental conditions to be controlled include body site, gender and type of hearing. The experimental methodology is also discussed.

2.2.1 Participant considerations

Practical choices of body sites using the more sensitive glabrous skin were the fingertip for singers, whereas most musicians would need to use the sole of the foot as their hands are used to play their instrument (although some musicians also use their feet to play).

Many researchers have investigated the distal pad of the fingers (i.e. fingertips) because of their high sensitivity. Johansson and Vallbo [72] have reported that index and middle fingers have the largest density of rapidly adapting mechanoreceptive units, i.e. Meissner and Pacinian corpuscles. Research reviewed by Brisben *et al* [73] has reported approximately 2,400 Pacinian corpuscles in the human hand (about 350 per finger and 800 in the palm). The distribution of densities and response characteristics of Pacinian corpuscles on the sole of the foot is different but unclear to date [74]. Kennedy and Inglis [75] have reported 14 Pacinian corpuscles and 59 Meissner corpuscles on the sole of the foot. An earlier review by Bell *et al* [76] reported 2000 Pacinian corpuscles distributed across the human skin and one-third of them in the fingers and toes plus the fact that the amount of these corpuscles decreases considerably with age.

Munger and Ide [77], published a critical review on the physiological and morphological similarities between the Pacinian corpuscles and the hair cells of the cochlea. Earlier, Gault [78] believed that the skin could be trained to feel vibration on the basis that the eardrum is a membrane akin to the skin. However, Knudsen [79] claimed that the skin is much more crude than the ear. Gescheider [13, 80] has shown that the amplitude of psychophysical detection thresholds for the skin of the hand is much higher than that for the eardrum, which might be ameliorated through signal amplification. However, as discussed below, the restricted vibrotactile-frequency response provoked some reluctance to consider the skin as a potential channel to transmit the speech bandwidth.

The detection thresholds also depend on the temperature of the body sites tested [81]. As indicated by Bolanowski and Verrillo [82, 83], the detection thresholds provided by Meissner corpuscles up to 100Hz ar not affected by temperature changes between 15 and 40ºC in the palm of the hand using sinusoidal stimuli;

however, for Pacinian corpuscles, sensitivity from 100Hz can change markedly with temperature.

Another factor that can also affect detection thresholds is sensory adaptation. This produces a decrease in sensitivity that occurs after prolonged exposure to vibrotactile stimuli with a recovery time that may take up to several minutes depending on duration and intensity [22, 84]. Adaptation involves a complex relationship of neural mechanisms and perceptual effects, the latter being better understood [85]. The effect of prolonged stimulation at different suprathreshold levels has been reported in [32, 86, 87].

Participants' age and gender also have to be controlled. Kenshalo [88] tested participants with normal hearing and found the vibrotactile detection thresholds of 27 young persons aged 19 to 31 significantly different than those of 21 older participants aged 55 to 84 when using sinusoidal stimuli at 40 and 250Hz on the palm of the hand and the sole of the foot. Stuart *et al* [89] found significantly higher vibrotactile detection thresholds for sinusoidal stimuli of 30 and 200Hz at the forearm, the shoulder and the cheek between 22 young participants aged 17 to 27 years and 22 older participants aged at least 55 years, both groups having normal hearing; however, no significant difference was found at the pad of the fingertip.

Frisina and Gescheider [90] also tested participants with normal hearing and found significantly different sensitivity between detection thresholds on the palm of the hand of five adults aged 20 to 39 years and 7 children aged 8 to 11 years using sinusoidal stimuli of different durations; children were more sensitive than adults below 200Hz. Goble *et al* [91] used a different method and different gap sizes surrounding the contactor to stop waves propagating outside the area of interest. These researchers found a significant difference between detection thresholds from young and older participants with normal hearing measured at the index fingertip and throughout the range of sinusoidal stimuli between 10 and 400 Hz. There were 44 young participants aged 18 to 33 years and 8 older participants aged 57 years or older. In general, these findings support the known reduction in the amount of Pacinian corpuscles with age [76].

In addition, Verrillo [92] tested 12 men and 12 women with normal hearing and comparable age and were found to have similar detection sensitivity with the hand using sinusoidal stimuli between 25 and 700Hz, except that the sensitivity of women was higher with increased vibration intensity at 250Hz. At this frequency of maximum sensitivity, Gescheider *et al* [93] found that the detection thresholds in women varied significantly over their menstrual cycle, except when they were taking birth control pills. The threshold variation was gradual over periods of approximately two weeks.

Various authors [94-96] have found no significant difference in detection thresholds between participants with normal hearing and participants with hearing impairments. Donahue and Letowski [94] found that the mean thresholds of five participants with normal hearing tended to be lower than those of five participants with a severe/profound hearing loss in the range 32 to 500Hz using a commercially available vibrator for speech training strapped to the participant's wrist; however, the difference was non-significant.

2.2.2 Test methods

Classical psychophysical methods are still in use today [97]. However, adaptive methods have been introduced more recently and are widely used. These include the staircase method which is also referred as the method of up and downs or the Békésy audiometric method [98-100]. Depending on decision and termination rules, there are many types of staircase designs [101]. A recent review by Gandhi *et al* [102] discusses test methods and experimental conditions used for the measurement evaluation of detection thresholds. The review concludes that there is still no standardisation of the methodology among researchers despite the current international Standard ISO 13091-1 [103].

In the early 1990s, Verrillo and Gescheider [22] already noted the difficulty in making comparisons between studies of detection thresholds due to the different test methods and experimental conditions in different laboratories. In addition, different reference quantities in the definition of levels used to measure detection thresholds are reported across the literature. The current Standard for the preferred reference quantities [104] is the International System of Units. More recently, Harazin *et al* [105] and Maeda *et al* [106] established that the measurement repeatability of vibrotactile perception thresholds obtained with different systems was sufficient for diagnostic purposes only with the relevant Standard ISO 13091-1 [103].

In addition to the above participant considerations, equipment variables such as the type of transducer, its contactor and the user interface may also affect experimental procedures. The design of electromagnetic shakers which have been traditionally used for vibrotactile research considers mechanical properties of the skin as a transmission medium, reproduction quality and dynamic range [35]. The ability of a shaker to reproduce the waveform depends on factors such as bandwidth and linearity.

Boothroyd and Cawkwell [107] in 1969 compared detection thresholds at the fingertips of participants with normal hearing and with hearing impairments using bone conduction vibrators and a clinical audiometer and found that the thresholds varied considerably among participants. The contact area of the transducer, contact force, and the gap surrounding the contactor can significantly affect the measurement of detection thresholds [32, 108].

A comparison of equipment and parameters such as contactor configuration used for vibrotactile testing over the last decade or so is summarised by Gandhi *et al* [102]. Nowadays, there are commercially available vibrometers that use a contactor surround for automatically measuring vibrotactile thresholds up to 500 Hz on the fingertips or the feet (see for example the HVLab Tactile Vibrometer [109]). This surround is often used in clinical research to produce a threshold response in the non-Pacinian channels [110]. Figure 2.1 is the cross-sectional view of an experimental arrangement with the gap surrounding the contactor. Other studies [32, 91, 111] measured detection thresholds at various body sites without contactor surround and found that the lack of surround increases the threshold below approximately 40Hz and decreases it in the higher range. Van Doren [112] found also higher thresholds in the lower frequency range on the palm of the hand without the surround, except that the threshold in the higher frequency range up to 250Hz the threshold shape was maintained with and without surround.

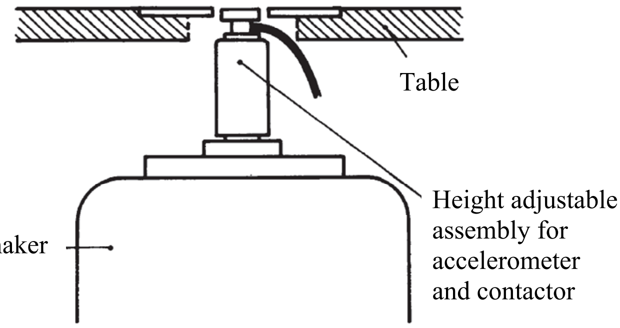

Figure 2.1 Sketch showing the contactor and its surround (reproduced from [111]).

The skin contactor is particularly important when the contactor has to push against larger volumes of the elastic skin medium and the indentation has to be maintained constant [35]. Verrillo and Bolanowski [23, 113] tested the effect of stimulus duration in combination with the effect of contactor size and found that sinusoidal bursts below 1s between 100 and 500Hz increased the detection threshold level on the palm of the hand markedly with respect to the threshold of burst durations of 1s with contactor areas of increasing size up to 2.9cm^2. That is, vibrotactile thresholds were detected as a function of burst duration with shorter bursts being harder to detect than longer ones.

These results matched the theory of temporal summation of stimulus energy over time on the skin receptors from the mathematical model that predicts the relationship between stimulus duration and intensity at the auditory detection threshold. Whilst this could be critical for the perception of music through the skin, it is noted that these are measurements at threshold and musicians would not be presented with music at threshold because it would be too demanding to concentrate on playing and feeling such low level vibrations.

In addition, Frisina and Gescheider [90] found a relatively small effect of the duration of stimuli at 25 and 40Hz for adults and children, though children thresholds showed marked temporal summation effects at 200Hz.

2.3 VIBROTACTILE PERCEPTION OF PITCH

Having discussed important factors in the detection of vibrotactile thresholds, this section discusses the potentially confounding effects of pitch and intensity using stimulation produced by electro-magnetic transducers, which can also affect the perception and discrimination of frequency. Training and applications of vibrotactile perception in music and other areas are also discussed.

2.3.1 Pitch and intensity

High vibration intensity above the vibrotactile detection threshold affects pitch perception [114, 115]. Like the ears, the skin has different sensitivity at different frequencies, except for low frequencies such as 25 and 40Hz [22]. Verrillo *et al* [116] showed that changes in subjective intensity for the skin are produced by equal sensation magnitude contours similar to the equal loudness contours which have been fundamental in the development of telephones.

The limitations of the skin to discriminate frequency aspects of speech have been reported by several researchers. Gescheider [13] showed that the range of speech frequencies was much larger than that for the skin capable of detecting frequencies up to approximately 1kHz. Moreover, the discrimination thresholds of changes in frequency of vibration up to about 300Hz for the ear were found to be much larger compared to those for the finger [117]. However, later results from Franzén and Nordmark [118] found a remarkable similarity between the frequency discrimination of the skin and the ear using trains of pulse frequencies up to about 384Hz, suggesting that the previous claims for poor discriminative capacity of the skin were no longer tenable.

Signal coding is a primary aspect to accomplish effective vibrotactile speech transmission. Summers *et al* [119] investigated the perception of changes in one-octave steps using vibrotactile stimulation at the fingertips of participants with normal hearing. From a practical point of view, different stimulus waveforms up to 400Hz accounted for the actual waveform variations that occur with limited bandwidth of some tactile aids in contrast to the ideal pure tones or conditions in a laboratory setting. In the pre-development of tactile vocoders, Rothenberger *et al* [120] encoded spectral information such as the fundamental frequency of voiced speech with single vibrotactile transducers using sinusoids and pulse frequencies applied to the palm of the hand and the forearm.

Temporal aspects related to pitch include an increased perception of stimulus onset- and offset with increasing pitch as reported by von Békésy [115]. Yuan *et* *al* [121] also performed experiments with the Tactuator on the temporal onset- and offset-order discrimination to investigate the communication of acoustic stimuli in tactile aids for profoundly deaf people. One of the locations tested was the fingertip of the middle finger of participants with normal hearing using pairs of sinusoidal stimuli up to 300Hz presented at different suprathreshold levels. Each stimulus in a pair was up to 0.5s long and corresponded to frequencies from different regions of the tactual sensory system. Thresholds were substantially higher for pairs that contained stimuli within the same frequency region compared to pairs that contained frequencies from different frequency regions.

This implies that stimulus onset is also important to recognise quality or timbre of musical instruments as in the auditory system [122]. An early indication that the sensory quality of vibrotactile frequencies below 100Hz was different compared to higher frequencies was already highlighted by Verrillo and Gescheider [22]. Recently, Russo *et al* [123] and Ammirante *et al* [124] found that the vibrotactile timbre of signals from musical instruments or voices can be differentiated through their fundamental frequency applied to the lower back of participants with normal hearing and with hearing impairments.

2.3.2 Training

Training is crucial for an effective use of vibrotactile devices and should be considered from the start of the design process [45]. Verrillo [61] and Galvin *et al* [125] have indicated a range of training variables to consider in the design and development of training programs. The training device will depend on the features to consider, e.g. physical dimensions and accessibility as well as the trainees using the device and their characteristics as discussed above. Rönnberg *et al* [126] found that the trainees' cognitive prerequisites of specific tactile aids were directly proportional to the effectiveness of vibrotactile speech training for people with hearing impairments. The training program may include general sequential stages such as detection, discrimination, identification and improvement in the performance of these tasks.

Rothenberg and Molitor [127] found that eight participants with normal hearing and five participants with profound deafness had similar ability to identify variations in voice fundamental frequency. However, it was suggested that the participants with profound deafness could undertake training to overcome their difference in vibrotactile pitch identification. Later, Donahue and Letowski [94] noted that the research on vibrotactile perception of people with hearing impairments was considerably limited in the mid 1980s and training methods were based on results from people with normal hearing. These researchers found a high percentage of correct responses in the vibrotactile test performance by participants with normal hearing and with hearing impairments using commercially available vibrators.

Plant [45] has considered the age of children and adults during training. Earlier, children with deafness that were trained in classrooms for months or even years could appreciate music and poetry via their fingertips using a Teletactor that incorporated a piano-unit and had portable and non-portable versions [38, 128].

There is seemingly little research on vibrotactile relative pitch (i.e. the ability to distinguish one musical note as being higher or lower than another) which is learned by most musicians to recognise intervals, and absolute pitch (i.e. the ability to identify the pitch of an isolated musical tone) which is usually acquired by fewer people. This is addressed in this thesis.

Vibrotactile gloves that incorporate small vibrating DC motors have been recently tested in a musical context [129]. Huang *et al* [130, 131] have recently tested a vibrotactile glove for training rhythmic fingering skills in order to play monophonic melodies on piano that were restricted to five pitches and notes of different durations with one motor per finger.

2.3.3 Musical applications

There are an increasing number of applications using vibrotactile sensation on hands and feet applied in a musical context for both people with normal hearing and with hearing impairments. Verrillo [132] already provided a base of knowledge about the possibilities for performing musicians to use vibrotactile sensations to supplement auditory cues as feedback signals.

New research examples include the Vibrato, a speaker connected to five different finger pads that allows people with hearing impairments to feel the difference between notes, rhythms and instrument combinations [133]. Techniques such as frequency transpositions, octave shift and modulating algorithms have been relatively successful for the detection and identification of vibrotactile stimuli using a violin [134]. Yoo *et al* [135] has investigated the perception of 80 vibrotactile two-note chords assessed by participants with normal hearing that could consistently describe vibrotactile consonance and dissonance. Yao *et al* [136] have tested vibrotactile shoes for dancers with hearing impairments that can perceive musical rhythm reflected by frequency and tempo reflected by the sequence and intensity of vibration stimuli.

Tactile devices based on electromechanical transduction for the consumer electronics market are discussed in [137, 138]. In addition, there are a broad variety of fields other than music where vibrotactile technology is currently applied. People with hearing impairments can detect and identify environmental sounds [139-141]. Wiciak and Mlynarczyk [142] have tested wave-vibration markers on the wrist of people with blindness for the determination of important and dangerous areas. Kim *et al* [143] have explored vibrotactile pattern recognition on the top of the foot wearing shoes with pre and post training using a vibrotactile display for driving safety information. Another example in the context of transportation and navigation that has tested the vibrotactile pattern identification and reaction times is given in [144]. Other application fields include entertainment and game environments [137], teleoperation and virtual environments [70], therapy and rehabilitation [145], medical training [146] and prosthetics [147].

2.4 SUMMARY

Over the 20th century, there have been numerous developments in tactile aids mostly used to transmit amplitude, frequency and temporal aspects of vibrotactile speech for people with hearing impairments and to complement the use of wearable hearing aids or education methods.

There is a high degree of similarity between the hearing system and the skin in aspects such as the frequency dependency of perceived intensity [116]. However, there are limitations in the perception of fine structure temporal and spectral aspects in relation to the identification of fast and complex acoustical features [53], which awaked scepticism about the skin capabilities as a transmission medium.

Electromagnetic shakers have been traditionally used for vibrotactile research due to their capabilities to match the frequency response and the dynamic range of the skin [35]. Among the choices of body sites to be tested, the fingertips are suitable in the present study due to their physiological characteristics and the available knowledge about them regarding sensitivity without using a contactor surround [32, 91, 111, 112] and standard test methods [103]. Although there is still limited psychophysical knowledge about the feet, they are also convenient for vibrotactile music performance. New findings using these body sites should provide research avenues of great potential for development and commercialisation in additional areas such as entertainment, navigation medical and virtual environments.

The coding of acoustic information into the vibrotactile domain along with adequate training has shown considerable advantages for the discrimination and identification of speech features to be explored in a musical context [38, 45]. In addition, a predominant amount of research evidence has shown a similar sensory capacity between people with normal hearing and with hearing impairments for the perception of thresholds in terms of amplitude or frequency [94-96, 127]. Although standard methods of measurement exist and are being developed [43, 71], they still need to be widely adopted for adequate comparison of results across different research centres [102].

As indicated by Verrillo [61], working in the field of vibrotactile perception and sensory substitution is a complex cross-disciplinary scenario with boundaries difficult to formulate. In this context, fruitful outcomes would ideally need team collaboration with expertise in fields such as speech and audiology, music psychology, psychophysics, human response to vibration, human physiology and neuropsychology.

3 APPARATUS AND EXPERIMENTAL SET-UPS

3.1 INTRODUCTION

This chapter describes the set-ups for the experiment on detection thresholds and for the two experiments on pitch perception, including how the equipment was calibrated and the objective measurements that were performed prior to running the psychophysical experiments on fingertips, forefeet and heels.

Considering the literature reviewed in Chapter 2, the experiments were designed to include electromagnetic shakers [35] and contactors without a surround gap [103, 135] rather than other coil configurations such as DC motors attached to gloves [129-131] or wristbands [142], or piezoelectric arrays of contactor pins for the fingertip [138] or attached to shoes [143]. This way, more solid and versatile set-ups were provided to test the detection of vibrotactile thresholds and to train participants in the discrimination and identification of vibrotactile pitch.

3.2 FINGERTIPS

3.2.1 Establishing vibrotactile detection thresholds

For the experiment using the fingertip of the middle finger to establish vibrotactile detection thresholds, test tones were presented to participants via a contactor disc on which their fingertip is placed. This design was based on set-ups such as the one presented in [111] in order to focus on the response of Pacinian corpuscles from vibration stimuli above approximately 40 or 50Hz with a relatively large contactor size and a relatively long stimuli duration, as suggested in [23, 113]. Limited ranges of temperature [81-83] and participants' age [76, 88, 89] were also considered, as discussed later regarding the subjective measurements that are presented in Chapter 4.

This section describes the procedures to measure the vibration levels of the test tones presented to the participants. Other objective measurements include masking noise conditions, background vibration, transfer function of the contactor disc and the effect of loading on the contactor disc. Figures 3.1 and 3.2 show the details of the experimental set-up. The items of equipment are listed below.

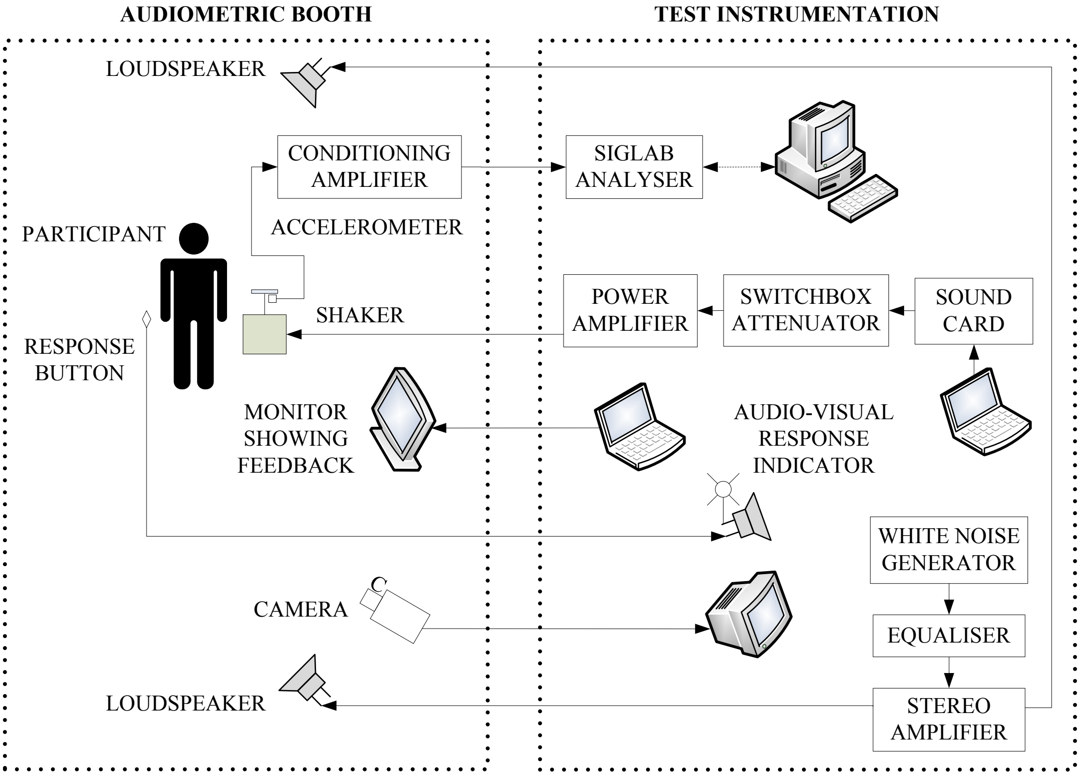

Figure 3.1 Diagram of experimental set-up.

Figure 3.2 General view of audiometric booth is shown (top left) along with details of the contactor disc and a participant's fingertip being tested.

The following equipment was on the experimenter's bench outside the audiometric booth (the items marked with an asterisk were used for calibration purposes):

- Laptop, Dell – Latitude D620 (for bespoke graphical user interface)
- Soundcard, SoundBlaster Creative Labs – type SB0270
- Switchbox attenuator, Standard telephones & cables – type 74616 GRP-A
- Power amplifier, Brüel & Kjær – type 2706
- DSP Siglab "virtual network analyser", DSP technology – type 20/42*
- Desktop PC, RM – type Accelerator*
- Calibration exciter, B&K – type 4294*
- Sound level calibrator, B&K – type 4231*
- Sound level meter, B&K – type 2231*
- Laptop, Toshiba pro 4600 (to display simple feedback to participants)
- Voltmeter, Velleman – type DVM890 (to monitor response from participants)
- Bespoke light emitting diode box
- Video monitor, Sanyo – CRT display M0NSB6
- Integrated stereo amplifier, Teac – type A-R650
- Audio frequency graphic equaliser, Soundcraftsmen – type 20-12A
- Bespoke white noise generator box (RS Components)
- Thermometer probe, RS 123-901 – type TH200 (for room temperature)
- Infrared thermometer, TENMA – type 72-6700 (for participant's temperature)
- Infrared thermometer, Fluke – type 61 (spare)

Equipment in the audiometric booth (i.e. Industrial Acoustics Company medical research examination chamber):

- Loudspeaker, Behringer – type Truth B2030P (2 units)
- Video camera, Panasonic – CCD 92B15468
- Video camera, Swann – type FC PNP-155 (spare)
- Video monitor, Sampo – LCD type SL7001
- Bespoke rapid-prototyped patient response button
- Patient response button, PC Werth – type AS1 215
- Earplugs, Howard Leight – type SNR 28 (to test occlusion effect)
- Hearing defenders, Peltor – type Optime III (to test occlusion effect)
- Shaker, Ling Dynamic Systems (LDS) V200 series – type 202*

- Microphone conditioning amplifier, B&K – type 2690*
- Accelerometer, B&K – type 4374* (2 units)
- Force transducer, B&K – type 8200
- Bespoke aluminium contactor disc, diameter: 2cm, thickness: 0.8cm
- Bespoke aluminium rod, diameter: 0.4cm, length: 6.5cm (to support contactor)

The aluminium contactor disc was flat with a thin washer beneath the disc to allow tight assemblage as well as a fixing point for the accelerometer, as shown in Figure 3.2 (bottom). The surface roughness for the contactor disc was estimated to have a centre line average of 3.175μm through visual and tactile tests according to the roughness inspection procedure described in the Standard ISO 4288 [148]. In line with methods of measurement at the fingertips from the Standard ISO 13091-1 [103] and [111], the height of the contactor disc was such that the fingertip rested upon it naturally.

Note that the shaker, rod and contactor did not touch the supporting table, which was also covered with resilient foam. This ensured that only the fingertip was exposed to the vibration signal and not the elbow and forearm of the participant that rested upon the table.

3.2.1.1 Calibration and measurements

The following set of measurements was used to check and calibrate the equipment. The calibration procedure checked all the equipment chain from the accelerometer to the display screen on the Siglab analyser. Before and after each measurement run, the accelerometer used to measure vibration levels was calibrated with the calibrator that produces an acceleration of $10ms^{-2}$ at 160Hz. The full set of measurements was periodically repeated approximately every other month during the initial stage of subjective testing of participants and at longer intervals afterwards to ensure there were no important changes.

A. Reference levels of test tones

The test tones were presented to the participant at different levels. For convenience, the levels were described using a dBV scale where the highest presented level was denoted as 0dBV (re: 1V) and this is referred to as reference level. The following procedure describes how the reference levels were obtained for each of the eleven test tones used in this experiment.

The test tones were the musical notes C and G over the five-octave range from C1 to C6. The frequency of each tone was calculated using the ratio $2^{1/12}$ for each of the 12 equal-tempered semitone intervals. Equation 3.1 was used to calculate the frequency of the n^{th} note relative to the musical note A4 [149-151]. These frequency values are referred to as scientific pitch [152-154].

$$f(n) = 440\left(\sqrt[12]{2}\right)^{n-49} \tag{3.1}$$

Each test tone was a pure tone synthesised in Matlab as a WAV file where:

$$x(t) = \hat{A}\sin(\omega t + \phi) \tag{3.2}$$

The WAV file was produced with peak amplitude $\hat{A} = 1$. The phase ϕ was 0° and ω was the angular frequency in rad/s (i.e. $2\pi f$) of a frequency f in Hz. The length t of each tone was adjusted to exact periodicity where $x(t) = 0$ in order to avoid abrupt termination of the signal.

Test tones were used to obtain reference levels for calibration checks at the beginning and end of each subjective test session. In order to obtain the reference levels, the range of gains was adjusted in the equipment chain to present the required intensity of stimulation to the fingertips during subjective measurements.

The volume settings of the laptop were kept to a medium level and the external sound card had the output gain fixed at a default value to avoid distortion. The attenuator switch with its load of 600Ω was set at 11.6dB. This provided the necessary headroom for the test on transient and continuous parts of high-pitched tones which needed to be increased in level to 10dB above the participants' detection thresholds. It was checked that the levels presented above the detection thresholds did not produce any signal overload. The gain of the shaker's power amplifier was set to approximately three-quarters of the control range without any additional attenuation.

The procedure to measure the reference levels included the use of the calibrator and mounting the accelerometer beneath the contactor disc with beeswax (see

Figure 3.2 bottom). The Siglab analyser displayed frequency-domain data with a resolution of 1.25Hz for the acceleration measured at the contactor disc. The power amplifier introduced very low-level harmonic distortion. The signal spectrum was checked by ensuring that the peaks of these harmonics were at least approximately 40dBVrms (re: 1Vrms) below the fundamental frequency. The linearity of the system was checked by ensuring that there was no distortion of the waveform in the time domain.

The reference levels are shown in Table 3.1. Before and after each subjective test session, these levels were checked as described above to ensure that they remained stable within approximately ±0.5dBVrms. Because both acceleration and displacement are used in the analysis, these are included in Table 3.1. The procedure to obtain acceleration and displacement is explained in the next section.

Table 3.1 Reference levels for the eleven test tones used in the experiment.

Note[a]	Frequency, Hz	Reference level[b], dBVrms (re: 1Vrms)	Acceleration[c]		Displacement[d]	
			ms^{-2} rms	dB (re: 10^{-6} ms^{-2})	μm rms	dB (re: 10^{-12} ms^{-2})
C1	32.70	−6.54	47.48	153.53	1124.72	181.02
G1	49.00	−3.99	63.68	156.08	671.81	176.54
C2	65.41	−4.82	57.88	155.25	342.65	170.70
G2	98.00	−5.50	53.52	154.57	141.15	162.99
C3	130.81	−5.67	52.48	154.40	77.69	157.81
G3	196.00	−5.53	53.33	154.54	35.17	150.92
C4	261.63	−6.28	48.92	153.79	18.10	145.16
G4	392.00	−8.04	39.95	152.03	6.59	136.37
C5	523.25	−7.24	43.80	152.83	4.05	132.15
G5	784.00	−8.92	36.10	151.15	1.49	123.45
C6	1046.50	−8.24	39.04	151.83	0.90	119.11

[a] Musical notes presented at the maximum level 0dBV (re: 1V).
[b] Acceleration level of the notes measured on the contactor disc in dBVrms (re: 1Vrms).
[c] Reference level expressed as acceleration in linear units and decibels (see Section B).
[d] Acceleration converted to displacement in linear units and decibels (see Section B).

B. Procedure to obtain acceleration values

The procedure to perform the subjective experiment followed the ascending method adapted from standard audiometric test methods [155]. The ascending method consists of a progressive reduction from a maximum stimulus level until no response is elicited by the participants. The stimulus level then ascends until a threshold can be detected by participants. The minimum change in the amplitude of the stimuli (i.e. test tones) was 2dBV on the tones synthesised as WAV files.

Detection thresholds were obtained in terms of root-mean-square (rms) acceleration which is the primary quantity for assessing human exposure to vibration according to Standards [103, 156]. Acceleration values were converted to displacement which is widely used in psychophysical studies for vibrotactile detection thresholds [91, 102, 110, 111].

In order to obtain acceleration values, the conditioning amplifier settings were for a gain of 0.01V/ms^{-2} and a sensitivity of 0.144pC/ms^{-2}. By way of an example for the accelerometer used, the calibrator reading as displayed on the Siglab analyser was −20.07dBVrms instead of −20dBVrms, i.e. the corresponding 10ms^{-2} that should be produced by the calibrator. Therefore the calibration *correction factor* was:

$$\frac{10^{\left(\frac{-20.07}{20}\right)}}{10^{\left(\frac{-20}{20}\right)}} = 0.99197 \tag{3.3}$$

For example, the reference level for tone C1 was −6.54dBVrms, as shown in Table 3.1. When this level was reduced by 2dBV for the tones synthesised as WAV files, the acceleration was:

$$\frac{10^{\left(\frac{-6.54-2}{20}\right)} \times correction\ factor}{0.01} = 37.71\ \text{ms}^{-2}\ \text{rms} \tag{3.4}$$

In addition, it was checked that the change in level in the test tones made the level at the contactor disc change the same amount. The average error magnitude of the change for all test tones at each level was < 0.4dBVrms, except for a few errors ≥ 0.5dBVrms marked in bold font in Table 3.2.

Table 3.2 Acceleration measured in dBVrms (re: 1Vrms) for four different levels of test tones described in dBV (re: 1V).

Note	0dBV	−20dBV			−40dBV			−60dBV		
	Measure (max.)	Measure	Change[a]	Error[b]	Measure	Change[a]	Error[b]	Measure	Change[a]	Error[b]
C1	−6.62	−26.26	−19.64	−0.36	−47.16	−40.54	**0.54**	−68.43	−61.81	**1.81**
G1	−4.05	−23.78	−19.73	−0.27	−43.45	−39.40	**−0.60**	−63.56	−59.51	**−0.49**
C2	−4.87	−24.57	−19.7	−0.30	−44.35	−39.48	**−0.52**	−64.90	−60.03	0.03
G2	−5.59	−25.44	−19.85	−0.15	−45.35	−39.76	−0.24	−65.48	−59.89	−0.11
C3	−5.74	−25.67	−19.93	−0.07	−45.65	−39.91	−0.09	−65.79	−60.05	0.05
G3	−5.58	−25.49	−19.91	−0.09	−45.48	−39.9	−0.10	−65.6	−60.02	0.02
C4	−6.33	−26.29	−19.96	−0.04	−46.28	−39.95	−0.05	−66.43	−60.10	0.10
G4	−7.98	−27.81	−19.83	−0.17	−47.77	−39.79	−0.21	−67.91	−59.93	−0.07
C5	−7.29	−27.17	−19.88	−0.12	−47.14	−39.85	−0.15	−67.24	−59.95	−0.05
G5	−8.89	−29.13	−20.24	0.24	−48.10	−39.21	**−0.79**	−67.58	−58.69	**−1.31**
C6	−8.32	−28.22	−19.90	−0.10	−48.12	−39.8	−0.20	−68.24	−59.92	−0.08

[a] Decrease in dBVrms from the maximum measured level.
[b] Error from the expected decrease of −20, −40 or −60dBVrms.

C. Masking noise and background vibration

Because audible airborne sound radiated by the shaker at the reference levels can significantly affect the measured threshold [157] broadband masking noise was used. In order to do this, the signal from the white noise generator was sent to the graphic equaliser. For the ten octave bands per channel (in the range from 20Hz to 20.5kHz) a minimum gain of −12dB was used for the first octave band from 20 to 40Hz, a gain of 10dB up to 320Hz and then smoothly rolling off up to 5.1kHz; the last two octave bands were set to a minimum gain of −12dB.

The following equipment was used to measure masking noise conditions in the audiometric booth:

- Sound quality head and torso simulator, B&K – type 4100
- Dual channel real-time frequency analyser, B&K – type 2144

Figure 3.3 shows the position of the simulator during measurements to simulate a realistic position adopted by participants during test sessions. Broadband masking noise (white noise) was presented via two loudspeakers that were symmetrically positioned in front of the participant. Masking noise level, background noise and levels radiated by the shaker and contactor disc were measured in one-third octave-bands. The level of masking noise averaged for both ears was 68dB L_{Aeq}

with ±1dB variation between the measurements. These were periodically repeated to ensure there were no important changes during the tests.

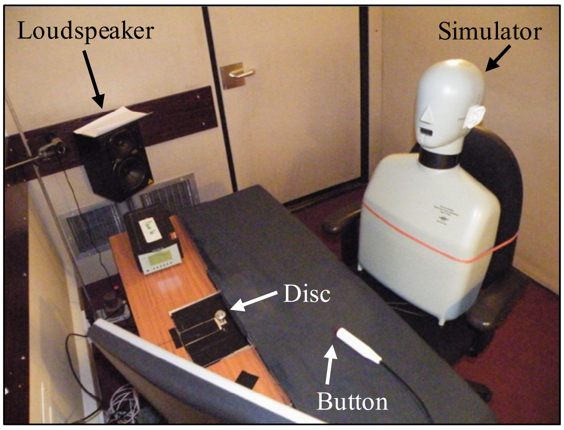

Figure 3.3 Measurement of masking noise conditions for experimental set-up (cf. Figure 3.2).

Figure 3.4 compares the measured spectrum with the hearing threshold taken from [158]. Figure 3.4 indicates that there were three tones below 100Hz where the radiated sound from the shaker was close to, or louder than the masking noise level. However, this was not problematic for these three tones because thresholds were always detected considerably below the maximum levels (typically at least 20dB lower) and these levels were close to the ISO hearing threshold.

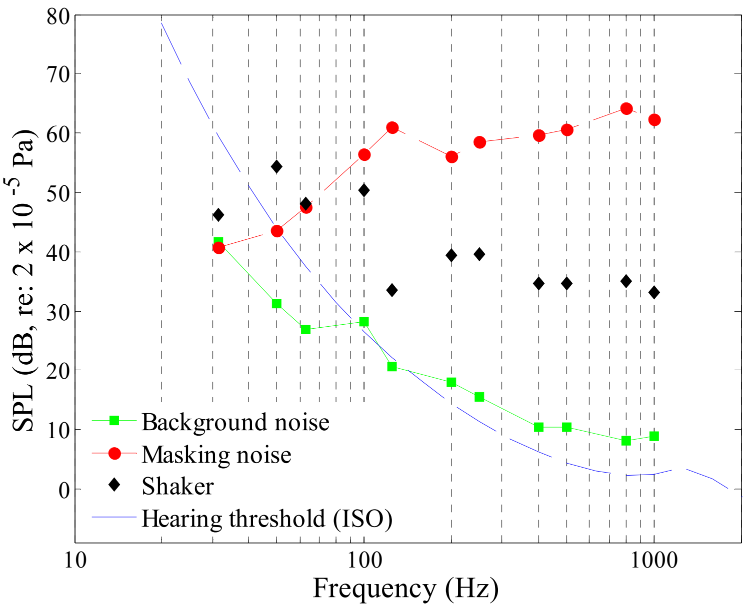

Figure 3.4 Comparison of masking noise with background noise, radiated sound by the shaker at maximum output and the hearing threshold from ISO 226:2003.

In addition, maximum levels were presented only once at the beginning of the procedure for the subjective measurements. The masking noise for all tones was subjectively checked and all tones were considered inaudible by three volunteers prior to running the subjective tests.

To assess the background vibration in the audiometric booth, the Siglab analyser was used to measure vibration on the contactor disc when there were no people inside the booth. The accelerometer was mounted underneath the washer using beeswax. The lowest background level that was measured in the range 20Hz to 2kHz was approximately –100dBVrms which indicated sufficient vibration isolation from the rest of the building.

D. Transfer function of contactor disc

During the experiment, it was not possible to measure the vibration on the top surface of the contactor disc as this was covered by the participant's finger. For this reason, a transfer function was measured from the permanent accelerometer position on the underside of the contactor to the top surface of the contactor.

The transfer function of the contactor disc was measured using the Siglab analyser to generate broadband noise. A total of 1601 frequency points were sampled at $F_s = 5.12\text{kHz}$ and averaged over 20 counts. A resolution of 1.25Hz for each frequency point provided a spectrum up to 2kHz. The accelerometer mounted beneath the contactor disc was used to measure the reference acceleration a_1 of the transfer function; another accelerometer of the same type mounted on the centre of the upper surface of the contactor was used to measure the acceleration a_2.

The transfer function magnitude of the contactor disc was found to be relatively flat with values within ±1dB across the range of test tones from C1 (32.7Hz) to C6 (1046.5Hz), except for the peaks and troughs presented in the vicinity of 422Hz and 833Hz (Figure 3.5). The reason for these features was not identified. However, the vertical dotted lines in Figure 3.5 indicate that the test tones G4 (392Hz) and G5 (784Hz), which were relatively close to the frequency region of the peaks and troughs, were not significantly affected.

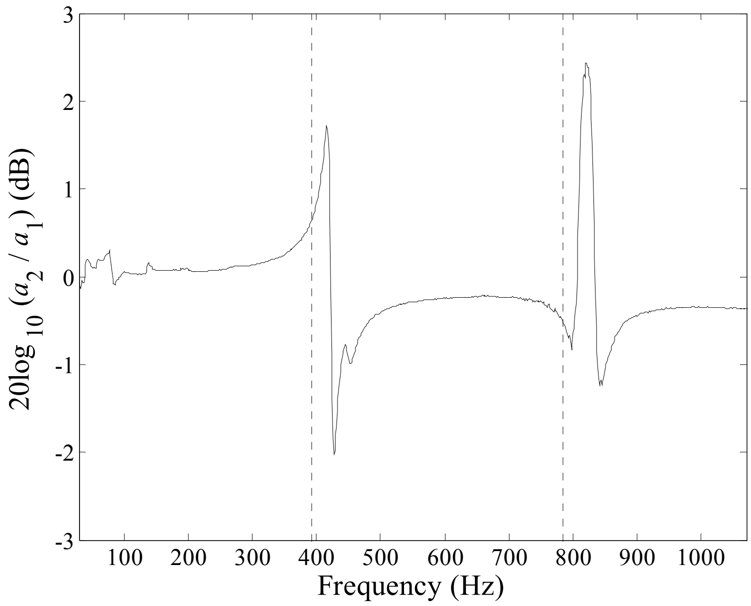

Figure 3.5 Transfer function magnitude for the contactor disc.

E. Force measurements

The effect of participants pressing down on the disc with their fingertip was assessed using the accelerometer underneath the disc. The change of acceleration due to pressing lightly compared to without any finger on the disc was 0.5dB on average across the range of test tones. It was deemed that this would not affect the measurement of detection thresholds during subjective tests.

3.2.2 Relative pitch discrimination and learning

Figure 3.6 shows a block diagram and details of the experimental set-up for which a range of training variables were considered for the development of learning through training, as suggested in [61, 125]. Apart from the shaker configuration, other design variables included the accessibility of the training device, user characteristics, type and amount of training, response formats and evaluation characteristics as discussed later regarding the subjective measurements that are presented in Chapter 5.

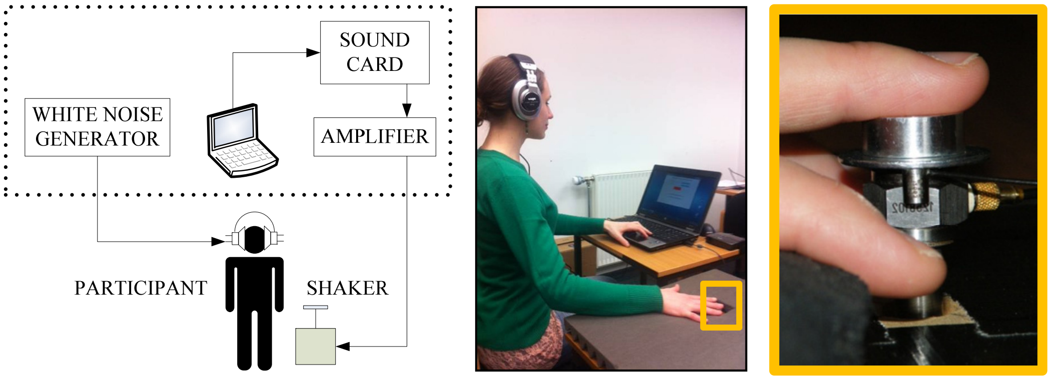

Figure 3.6 Diagram (left) and details (right) of portable experimental set-up with a participant being tested.

The items of equipment are listed below.

- Shaker, LDS, V200 Series – type 201/203
- Infrared thermometer, TENMA – type 72-6700
- Infrared thermometer, Fluke – type 61
- Notebook PC, HP – ProBook 6555b
- Sound card, Trust – 5.1 surround
- Power amplifier, Clever little box – four-channel 4 x 12W
- AC-DC power supply, Powerpax – type PTD-1250P
- MP3 player, SWEEX – Clipz 4 GB (used as white noise generator)
- Stereo Headphones, Yoga – CD-98

For calibration purposes, the below items of equipment were used.

- Dual channel real-time frequency analyser, B&K – type 2144
- Sound Level Calibrator, B&K – type 4231
- Calibration exciter, B&K – type 4294
- Accelerometer, B&K – type 4393

The masking noise provided through the headphones was measured using the equipment described in Section 3.2.1.1.C.

3.2.3 Learning relative and absolute vibrotactile pitch

This experiment used a two-octave electronic piano (ION Discover Keyboard USB) that was reconfigured so that each key press produced QWERTY code (i.e. standard computer keyboard output) instead of a musical signal. Essentially, the original microcontroller from the piano was replaced by a microcontroller of a standard computer keyboard. This allowed for mapping QWERTY code from the piano to the graphical user interface used in this experiment which is explained in Chapter 6 (see Figure 3.7).

The use of a piano unit on a portable experimental set-up was in line with previous research using the Teletactor [38, 128] which was previously used to train children with deafness for the appreciation of music and poetry via their fingertips. In addition, the stimuli used in the present study were similar to those reported recently with regard to melodies played on piano that are restricted to five pitches only [130, 131].

The remaining items of equipment and the objective measurements for this experiment were similar to those from the experiment on relative pitch discrimination in Section 3.2.2.

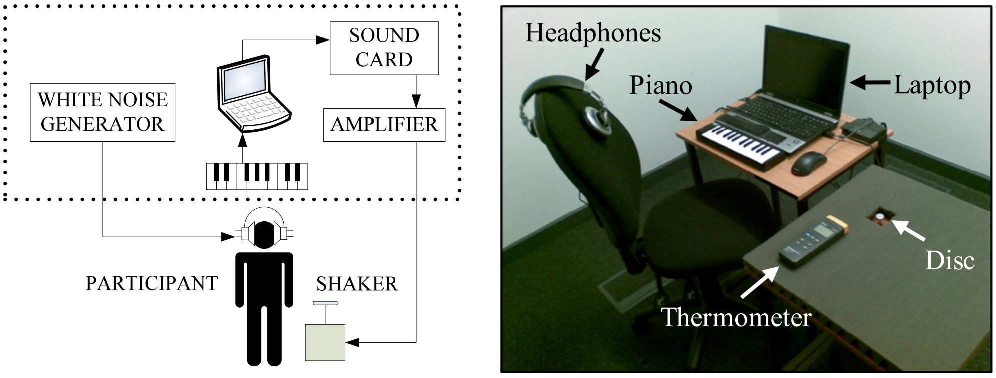

Figure 3.7 Diagram (left) and details (right) of experimental set-up with electronic piano keyboard.

3.3 FEET

3.3.1 Establishing vibrotactile detection thresholds

For the vibrotactile experiment using the feet, in line with the above experimental design to measure on the fingertip, this section describes the measurements of reference levels of test tones, masking noise conditions and vibration on the participant’s seat. In addition, larger contactor discs were used to measure transfer functions, vibration uniformity over the contact area and the foot load that had to be maintained constant with larger volumes of skin [35].

The semi-anechoic chamber that was used to measure detection thresholds on feet was adjacent to the audiometric booth that was used to measure detection thresholds on fingertips. As a result, some of the equipment to measure on fingertips was also used to measure on feet. The experimental set-up is shown in Figures 3.8 and 3.9. For brevity, only the new main items of equipment are listed below.

New equipment on experimenter's bench:

- Analogue mixing desk, Mackie – Onyx 1620i Premium
- Power amplifier, Acoustical Mfg Co Ltd – Quad 50E (2 units)

New equipment in semi-anechoic chamber:

- Loudspeaker (active nearfield monitor), Fostex – type PM1 MkII (2 units)
- Video camera, Panasonic – CCD 92B15468
- Accelerometer, B&K – type 4393 (2 units)
- Perspex contactor disc, diameter 12 cm, thickness 2.5 cm (used for forefeet)
- Perspex contactor disc, diameter 10 cm, thickness 2.5 cm (used for heel)
- Shaker, LDS – Type V406 M4-CE (2 units)
- Support trunnion (2 units) and auxiliary suspension (2 units) for shakers

The surface roughness for the Perspex contactor discs was estimated to have a centre line average of 1.6μm. As with the disc for the fingertip, this assessment was carried out according to the roughness inspection procedure described in the Standard ISO 4288 [148].

The auxiliary suspension consisted of a centralising and support system that adds stiffness to the standard shaker suspension. This way, the shaker can bear safely the heavy static load of the participants' feet. Extra care was taken to ensure an appropriate separation distance between both shakers to avoid transfer of vibration between them during each test. This is indicated by the yellow arrows in Figure 3.9. For ergonomic purposes, there is an inclination for the horizontal of 10° for the bottom shaker (left-hand side of the photo) and 25° for the top shaker (right-hand side of the photo).

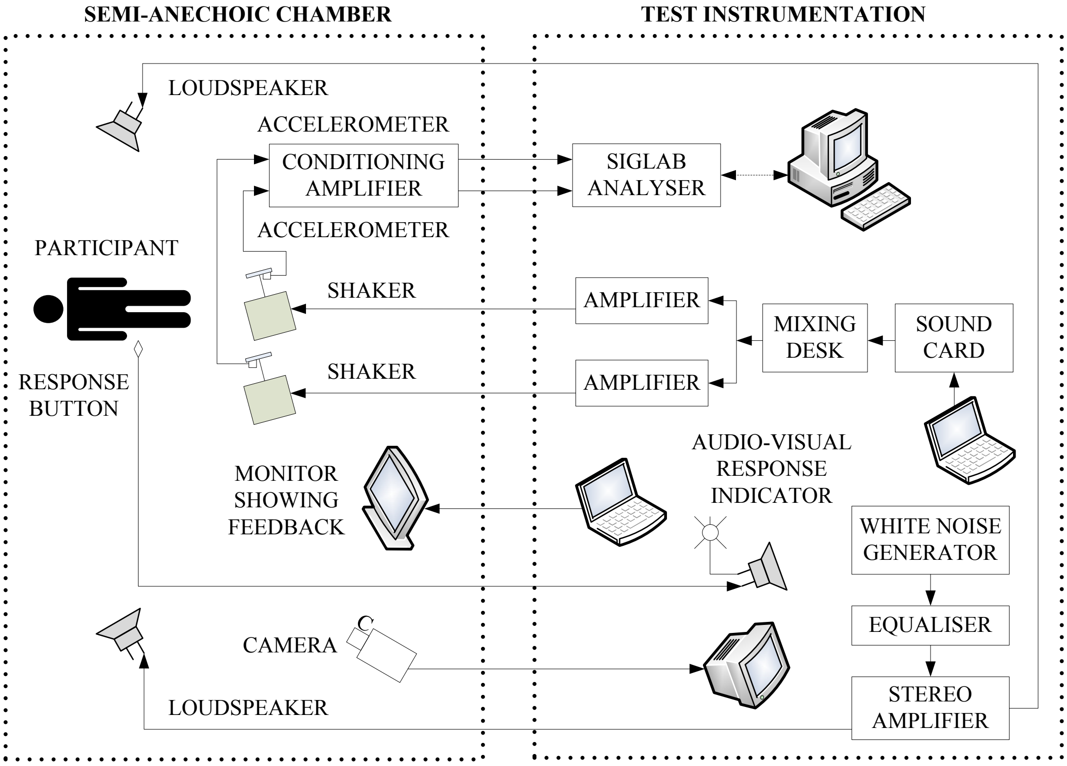

Figure 3.8 Diagram of experimental set-up.

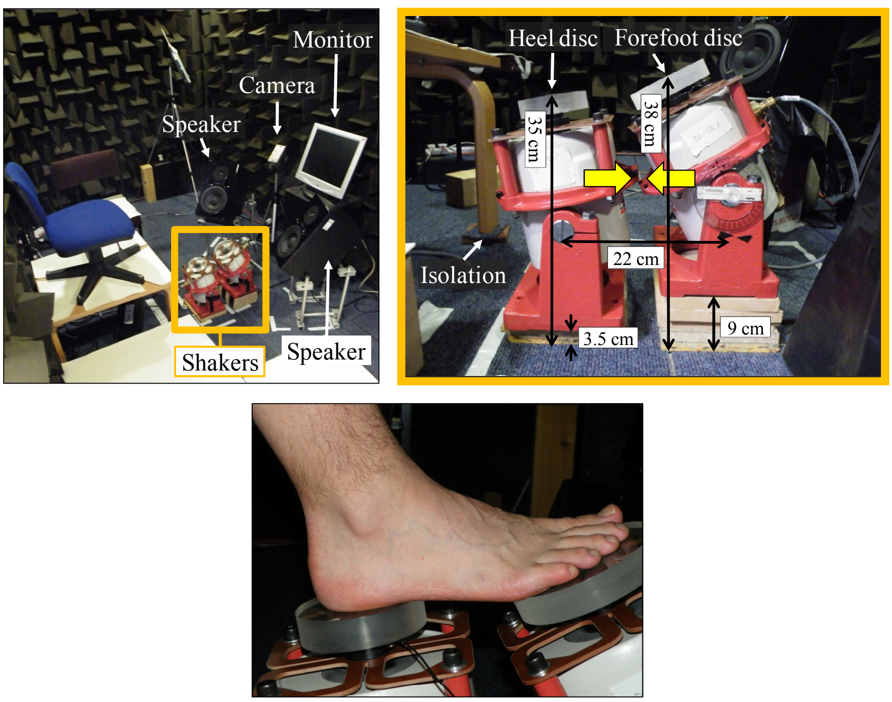

Figure 3.9 General view of semi-anechoic chamber is shown (top left) along with details of the shakers, contactor discs and a participant's foot being tested. Distances are shown on the top right graphic.

3.3.1.1 Calibration and measurements

As with the experimental set-up for the fingertips, the objective measurements described below were performed before running the subjective testing of participants. A two-channel system was used on this occasion. Channel one was used for the forefoot and channel two for the heel.

A. Reference levels of test tones

The test tones were generated and prepared in a similar way as in the experimental set-up for detection thresholds on fingertips. The measurement procedure to obtain the reference levels for calibration routines was also similar. The chain of equipment levels was adjusted; some settings remained as in Section 3.2.1.1 with the new settings described in this section. For the two channels used on the mixing desk, the gain was set to 40dB; each fader level was set to unity gain and the common main mix to 5dB.

Both signal spectrum and linearity were checked as before. Spectral coherence was also measured by comparing the signal at the output of the sound card (i.e. system input) with the signal at the contactor discs (i.e. system output). The coherence function examines the relation between these two signals and was always equal to one for the entire set of test tones at the reference level 0dBV. This indicated that the system output was fully related to the system input, without noise affecting the measurements.

The procedure to measure the reference levels included the use of the calibrator and mounting the accelerometer beneath the contactor disc. Accelerometers were mounted approximately 1.3cm from the disc edge towards the top right of the disc as seen from the participants' sitting position. As with the tests on fingertips, the measurements were checked before and after each subjective test session to ensure that they remained stable within approximately ±0.5dBVrms of the required levels. The reference levels are shown in Tables A.1 and A.2 of Appendix A.

B. Masking noise

An important aspect in the procedure to test the feet was that larger shakers and contactor discs increased the radiation of sound levels, which required more careful consideration of masking conditions using broadband masking noise (white noise). A sound level meter was used with its microphone set to *free field* and positioned azimuthally at approximately 45° pointing at the volunteer's ear as shown in Figure 3.10. The microphone was raised 1.5m above the floor. The level of masking noise was 68dB L_{Aeq} ±0.5dB which was subjectively tested by a few participants to ensure that masking noise was effective. There was only a difference of 1.5dB L_{eq} between low-frequency and high-frequency test tones presented at the reference level 0dBV when measuring azimuthally either at 0° (i.e. at the participant's nose position) or at 90° (i.e. at the position of the ear). Figure 3.11 shows the measured levels.

Figure 3.10 Measurement of masking noise conditions for experimental set-up.

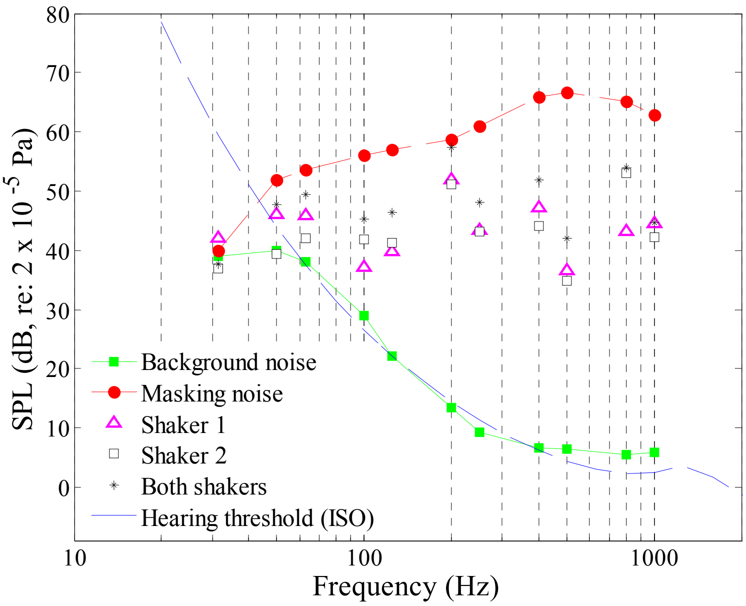

Figure 3.11 Masking conditions (hearing threshold taken from ISO 226:2003 [158]).

Compared to the set-up for the fingertips, Figure 3.11 shows increased levels of sound radiated by the shakers and contactor discs; hence higher levels of masking noise were needed below 100Hz (cf. Figure 3.4). This was primarily because of the larger contactor discs and the fact that the room and the loudspeakers were different from those in the set-up for fingertips.

Although air-borne masking noise has no effect on vibrotactile thresholds [157], it may be noted that relatively high levels of masking noise might affect some participants who are very sensitive due to physical conditions such as pregnancy or auditory conditions such as tinnitus and Ménière's disease which may affect hearing and the sense of balance.

C. Vibration on the participant's seat

Checks were carried out to ensure that the shakers did not induce considerable vibration levels on the participant's seat. To avoid such a problem, thick dynamically soft material for isolation was used under the wooden legs of the pedestal that supported the participant's seat, which can be seen in Figure 3.9 (top right). The vibration on the seat was measured when both shakers were simultaneously active. During these measurements no other signal was present and the accelerometer was mounted beneath the seat to measure the vibration with the participant sitting in the position shown in Figure 3.10.

The levels on the seat for the entire set of test tones reproduced at reference level were –76dBVrms on average with maximum and minimum levels measured as –55.6dBVrms and –91dBVrms which indicated sufficient vibration isolation. These levels were at least 60dBVrms below the level presented to the foot. Prior to running the subjective tests, these levels were tested by a few volunteers who confirmed that no vibration was perceivable via the seat.

D. Transfer function of contactor discs

The transfer functions of each contactor disc were measured with the same settings on the Siglab analyser that were used to measure the transfer function on the contactor disc for the fingertips. The accelerometer mounted beneath the disc was used to measure the reference acceleration a_1 of the transfer function; another accelerometer of the same type mounted on the centre of the disc top was used to measure the acceleration a_2. The accelerometers were mounted at approximately 1.3cm from the disc edge towards the top right of the disc as seen from the participants' sitting position.

The transfer function magnitude of the contactor discs was found to be relatively flat across the entire set of test tones C1 (32.7Hz) to C6 (1046.5Hz). The trough presented at 610.5Hz on the contactor disc for the forefoot did not affect the measurement of the test tones C5 (523.2Hz) and G5 (784Hz), which were the closest to the frequency region of the trough, as indicated by the vertical dotted lines in Figure 3.12. These results indicate that measuring on the underside is valid and the contactor discs reproduce the entire set of test tones without any considerable change.

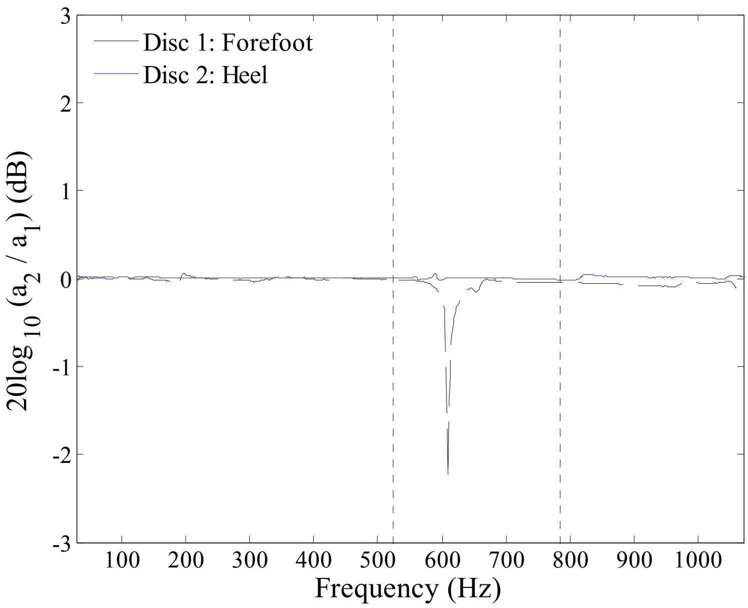

Figure 3.12 Transfer function magnitude for each contactor disc.

E. Vibration uniformity on contactor discs

Due to the relatively large size of contactor discs, tests were performed to assess the uniformity of the vibration over their surface. Figures 3.13 and 3.14 show the vibration uniformity on the contactor discs, which was measured with the same settings on the Siglab analyser as in the previous section. The accelerometer was mounted on the upper surface of the discs at three concentric positions, namely two o'clock (i.e. position 1), six o'clock (i.e. position 2) and ten o'clock (i.e. position 3) viewed from the participants' sitting position. Each position was approximately 1.3cm from the disc edge. Position 4 corresponded to the measurement with the accelerometer mounted in the centre of the disc on the upper surface.

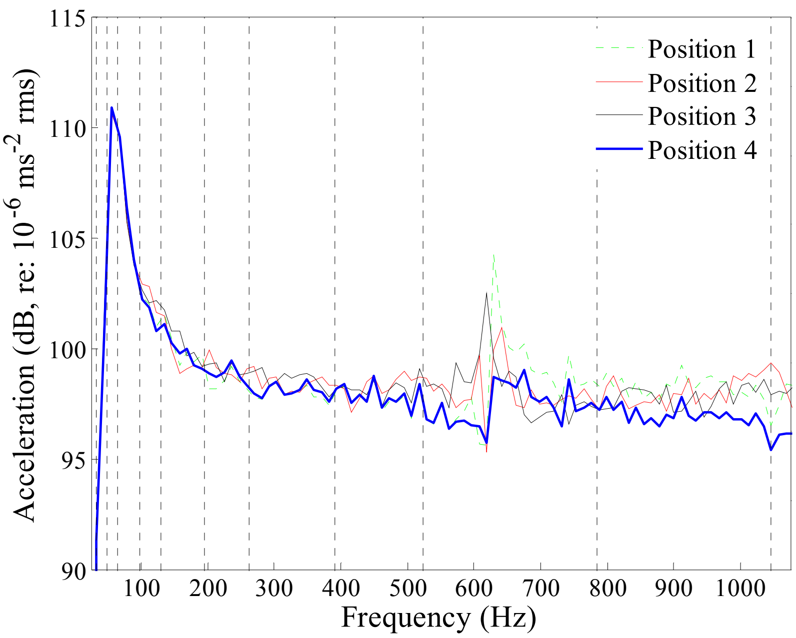

Figure 3.13 Vibration uniformity on the contactor disc used for the *forefoot* in terms of acceleration measured at four positions. The eleven test tones are indicated by the vertical dotted lines.

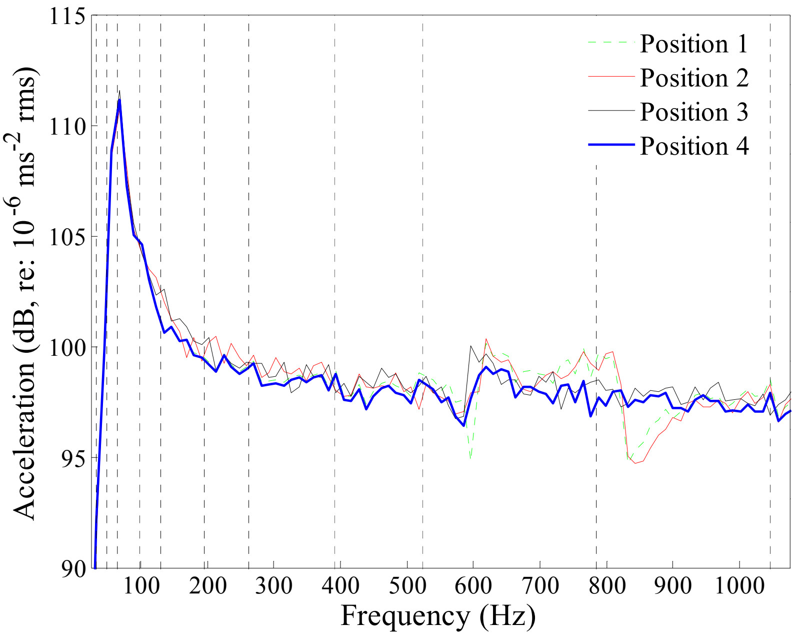

Figure 3.14 Vibration uniformity on the contactor disc used for the *heel* in terms of acceleration measured at four positions. The eleven test tones are indicated by the vertical dotted lines.

In general, Figures 3.13 and 3.14 show satisfactory uniformity within approximately ±2dB between the four positions for all tones presented in the experiments. However, there were frequency ranges with significant variation (e.g. in the vicinity of 620Hz on the disc for the forefoot), but these did not correspond to frequencies of the test tones.

F. Foot load on contactor discs

The effect of participants pressing down on the contactor discs with the foot was measured in order to establish the effect that this would have in the measurement of detection thresholds. The shakers incorporated a suspension system to try and minimise any effect, but the change of acceleration levels due to pressing lightly compared to without placing the foot on the disc was still found to be considerable for some test tones. Consequently, the reduction in acceleration level for some test tones required compensation.

The effect of foot load was measured by mounting the accelerometer beneath the corresponding disc, as close as possible to the centre of the disc. Initial tests were performed on four volunteers who had a variety of stature, foot size and weight. The difference between no load and load on each contactor disc was repeated twice for each volunteer and for the entire set of test tones presented at reference level. The average obtained from each pair of measurements at each tone and for each volunteer was chosen in order to compensate the values obtained during each subjective test session.

This revealed that compensation was needed for the first three test tones C1 to C2 (32.7Hz to 65.4Hz) when using the disc for the forefoot and for the first five test tones in the range C1 to C3 (32.7Hz to 130.8Hz) when using the disc for the heel. A calibration procedure was therefore carried out before and after each test session for these test tones in order to obtain personalised measurements on the forefoot or the heel of each participant.

Table A.3 in Appendix A includes additional measurements showing the difference between no load and load on each contactor disc as the levels for presentation of stimuli are reduced.

G. Procedure to obtain acceleration values

The procedure to obtain acceleration values was the same as with the measurements on the fingertips, except for the additional correction of measurements which was required due to the load of the feet that shakers and contactor discs had to bear. This personalised correction in the calculation of acceleration will be described as a part of the subjective measurements that were taken for each participant before and after each test session (see Sections 4.3.2.1 and 4.3.2.2 of Chapter 4).

3.3.2 Relative pitch discrimination and learning

Figure 3.15 shows a combination of the previous experimental set-ups for forefeet (cf. Figure 3.9) and fingertips (cf. Figure 3.6).

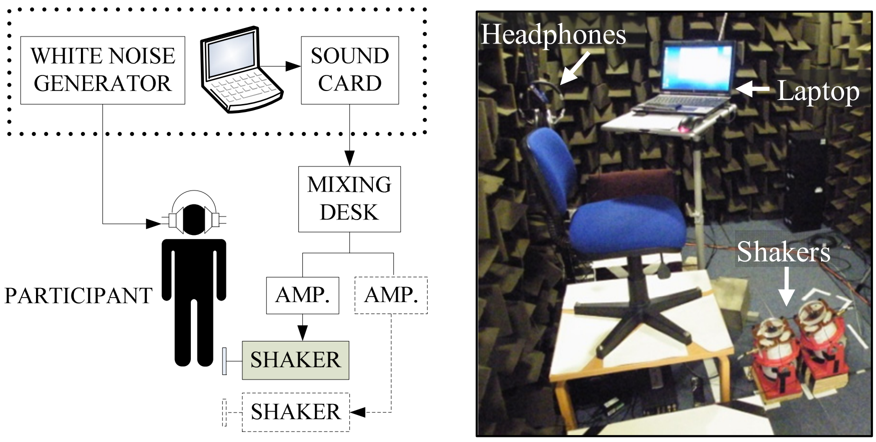

Figure 3.15 Diagram (left) and details (right) of experimental set-up in semi-anechoic chamber.

The combination of equipment items from the previous set-ups is listed below for clarity. The items used for calibration purposes were the same as those included in Section 3.2.2.

Equipment on experimenter's bench:

- Analogue mixing desk, Mackie – Onyx 1620i Premium
- Power amplifier, Acoustical Mfg Co Ltd – Quad 50E (2 units)

Equipment in semi-anechoic chamber:

- Notebook PC, HP – ProBook 6555b

- Stereo Headphones, Yoga – CD-98
- Sound card, Trust – 5.1 surround
- Infrared thermometer, Fluke-61
- Shaker, LDS – Type V406 M4-CE (2 units)
- Support trunnion (2 units) and auxiliary suspension (2 units) for shakers
- Perspex contactor disc, diameter 12 cm, thickness 2.5 cm (used for forefeet)
- Perspex contactor disc, diameter 10 cm, thickness 2.5 cm (used for heel)

The shaker for the heel was not active because it was only used to support the participants' heel. The objective measurements for this experiment corresponded to those performed for the experiment on detection thresholds on feet, as explained in Sections 3.3.1.1.C to 3.3.1.1.E. Additional objective measurements for this experiment on relative pitch discrimination depend on subjective measurements for the experiment on detection thresholds described in Chapter 4. Therefore, further measurements for the experiment on relative pitch discrimination are subsequently described in Chapter 5.

3.3.3 Learning relative and absolute vibrotactile pitch

As with the set-up described in Section 3.2.3 to test relative and absolute pitch identification on fingertips, and in line with recent research on vibrotactile training with the foot [143], this uses the same digital piano keyboard (see Figure 3.16).

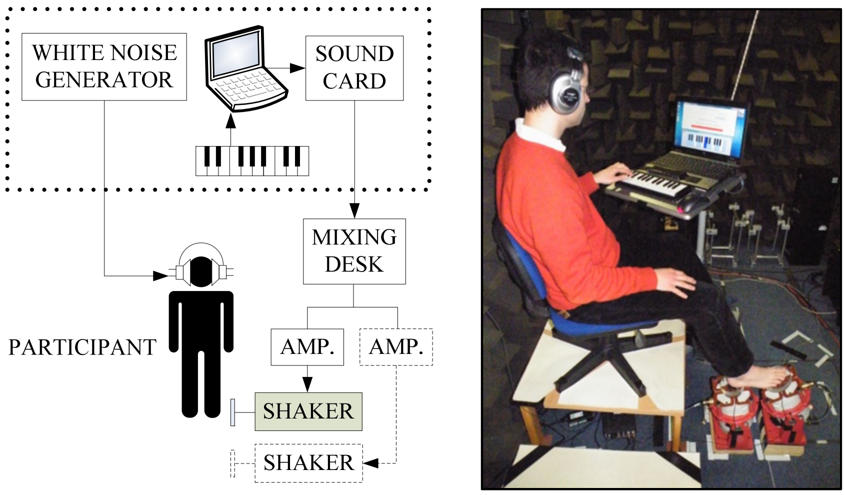

Figure 3.16 Diagram (left) and details (right) of experimental set-up in semi-anechoic chamber with the piano keyboard and a participant being tested.

The items used for calibration purposes were the same as in Section 3.2.2. The remaining items of equipment and the objective measurements for this experiment were similar to those in the preceding Section 3.3.2.

3.4 SUMMARY

This chapter described the equipment and its application in the experimental set-ups so that readers can follow and reproduce the design and the procedures used for objective measurements. The experimental equipment included electromagnetic shakers without using a contactor surround for detection thresholds and pitch perception on the fingertip, forefoot and heel.

In the experimental set-up for the fingertip, reference levels were determined for eleven tones over a five-octave range representing notes C1 (32.7Hz) to C6 (1046.5Hz) that were presented as test tones to participants. The measurements were performed in an audiometric booth that was highly isolated from vibration in the building. Broadband masking noise was used to mask the sound radiated from the shaker and contactor disc.

The measurements for the forefoot and the heel were carried out in a semi-anechoic chamber that was also isolated from vibration in the building. Broadband masking noise was essential due to the higher levels of sound radiated from the large shakers and large contactor discs. The vibration uniformity over the surface of the large contactor discs for the foot was relatively flat for the test tones. The loading from participants' feet on the contactor discs was found to be critical; hence the acceleration levels were corrected for each participant.

In general, solid and versatile experimental set-ups were provided for the present study. They underwent periodic calibration checks and were found stable and the measurements were sufficiently accurate to obtain reliable results. The intensity of test stimuli can be carefully controlled for accurate pitch assessment during subjective tests and in practical situations. Test stimuli of 1s duration were suitable according to standard methods to test detection thresholds. This also applies to the new training methods that were implemented to test the discrimination and identification of vibrotactile pitch. The detailed results and procedural aspects of these experiments are discussed in Chapters 4 to 6.

4 ESTABLISHING DETECTION THRESHOLDS

4.1 INTRODUCTION

This chapter concerns the experimental work that was designed to establish vibrotactile detection thresholds on three body locations: (1) the *fingertip*, i.e. on the surface of the whorl, arch or loop on the distal phalanx of the middle finger (see Figure 3.2); (2) the *forefoot*, i.e. on the distal part of the plantar side of the foot involving the distal and proximal phalanxes and partially the metatarsal bones (see Figure 3.9); and (3) the *heel*, i.e. on the proximal part of the plantar side of the foot, underneath the calcaneous bone (see Figure 3.9). The main sections of the chapter describe the type of participants, the objective and subjective measurement procedures for each test session and the results with analysis and discussion.

Based on the research questions in Section 1.2.1 of Chapter 1, the experimental work had six aims: (1) to establish the mean detection threshold for fingertips, forefeet and heels; (2) to determine whether or not the occlusion of the ear canal affects measurements of detection thresholds on the fingertips; (3) to determine whether or not mean detection thresholds for the fingertips are different for participants with normal hearing and with hearing impairments; (4) to determine whether or not the mean detection thresholds for the fingertips, forefeet and heels are different for participants with normal hearing; (5) to quantify the vibrotactile dynamic range that could be used safely; and (6) to investigate vibrotactile perception using the fingertips for continuous and transient parts of high-frequency tones.

4.2 PARTICIPANTS

None of the participants had a self-reported impairment of sensation in their hands or feet. The validity of test sessions was based on the verification stage at the end of the procedure to measure detection thresholds, as described in Section 4.3.1.2.A. If the results and the skin temperature were within tolerance, the results were deemed valid and included in the analysis. Considering the literature reviewed in Chapter 2 [76, 88-91], the participants' age and gender were also controlled as well as their musical skills and these data are included below. However, the samples of participants used in the analysis of experimental data were regarded independently of skin temperature, age, gender and cognitive or musical skills.

Approval for the experiment was given by the Research Ethics Committee of the University of Liverpool. The ethics documentation (advertisement, information sheet and consent form) are in Appendix B, in Sections B.1.1, B.1.2 and B.1.3, respectively.

4.2.1 Fingertips

For the fingertips, a summary of the participants tested is shown in Tables 4.1 to 4.3. In total, 105 test sessions were performed on a total of 58 participants including those with normal hearing and with hearing impairments.

For participants with normal hearing, valid results were obtained from the fingertip of the middle finger of the right hand from 32 participants (13 female and 19 male), as shown in Table 4.1. The age of these participants was in the range 18 to 65 years ($\text{mean:} M = 30.6, \text{standard deviation:} \sigma = 9.2$). Only 1 participant was aged 65 years and 1 participant was aged 50 years, 4 participants were aged between 38 and 41 years, 5 participants were aged between 33 and 35 years and the remaining 21 participants were aged between 18 and 29 years. The participants were all right-handed, except one participant who was left-handed. All these participants carried out a valid test using the right hand.

In addition, valid results obtained from the fingertip of the middle finger of the left hand were obtained from 17 participants (8 female and 9 male), as shown in Table 4.1. The age of these participants was in the range 22 to 65 years ($M = 32$, $\sigma = 11.4$). Only 1 participant was aged 65 years and 1 participant was aged 50 years, 2 participants were aged between 40 and 41 years, 2 participants were aged between 33 and 34 years and the remaining 11 participants were aged between 22 and 29 years. The participants were all right-handed, except one participant who was left-handed. All these participants carried out a valid test using the left hand.

The entire set of 42 participants was tested with no payment. Note that approximately three-quarters (or 78%) of the sessions were deemed valid.

Table 4.1 Sessions to measure detection thresholds via the middle fingertip of participants with normal hearing.

<table>
<tr><td rowspan="2">• No. of participants: 42

• No. of sessions: 64
• Valid sessions: 49
• Invalid sessions: 15</td><td>Right hand</td><td>• Sessions: 41
• Valid sessions: 32 (13 female, 19 male)
• Invalid sessions: 9 (6 female, 3 male)</td></tr>
<tr><td>Left hand</td><td>• Sessions: 23
• Valid sessions: 17 (8 female, 9 male)
• Invalid sessions: 6 (3 female, 3 male)</td></tr>
</table>

In order to investigate the perception of both transient and continuous parts of test tones, 14 participants were recruited out of the 42 above participants with normal hearing. The age of these participants was in the range 25 to 65 years ($M = 34.7$, $\sigma = 10.8$). Only 1 participant was aged 65 years and 1 participant was aged 50 years, 2 participants were aged between 40 and 41 years, 3 participants were aged between 33 and 34 years and the remaining 7 participants were aged between 25 and 29 years. Participants were right-handed and carried out the experiment using the right hand.

In order to assess the repeatability of the results, six male participants were recruited to perform two extra valid sessions per participant (see Table 4.2). The six participants were recruited out of the forty-two participants with normal hearing. The age of these participants was in the range 28 to 65 years ($M = 42.2$, $\sigma = 13.9$). Only 1 participant was aged 65 years and 1 participant was aged 50 years, 2 participants were aged between 40 and 41 years and 2 participants were aged between 30 and 31 years. These participants were right-handed and carried out the experiment using the right hand.

In order to test the occlusion effect, three participants out of the six aforementioned participants were recruited to perform two additional valid sessions per participant: one session using earplugs and one session using hearing defenders (see Table 4.2). Each session took place on a different day. The age of the three participants was in the range 40 to 50 years ($M = 43.7, \sigma = 5.51$).

Table 4.2 Additional sessions to assess results repeatability and occlusion effect via the middle fingertip of the right hand of participants with normal hearing.

• No. of participants: 6 • No. of sessions: 20 • Valid sessions: 18 • Invalid sessions: 2	• Sessions without ear plugs/hearing defenders: 13 • Sessions with ear plugs: 3 • Sessions with hearing defenders: 4

The hearing impairments of participants were self-reported according to the classification provided by the charity Action on Hearing Loss [2, 159] (formerly known as the Royal National Institute for the Deaf). These levels of hearing impairments were mild, moderate, severe and profound which are defined in Table B.1 and the questionnaire for participants in Section B.1.4 of Appendix B.

The main valid data to report were collected from eleven participants (8 female and 3 male), as shown in Table 4.3. One participant had a mild impairment, two participants had a moderate impairment, two participants had a severe impairment and six participants had a profound impairment that was acquired before the age of ten. All the hearing impairments were bilateral, except one of the participants who had unilateral profound impairment. The age for the eleven participants was in the range 23 to 67 years ($M = 40, \sigma = 14.6$). Only 1 participant was aged 67 years, 2 participants were aged 58 and the remaining 8 participants were aged between 23 and 45 years. All participants were right-handed and carried out the experiment using the middle finger of the right hand.

Two participants were paid £10 per test session and their travel expenses were reimbursed. Seven participants were reimbursed their travel expenses. The remaining two participants were tested with no payment.

Table 4.3 Sessions to measure detection thresholds using the middle fingertip of participants with hearing impairments.

• No. of participants: 16 • No. of sessions: 21 • Valid sessions: 13 • Invalid sessions: 8	Right hand	• Sessions: 16 • Valid sessions: 11 (8 female, 3 male) • Invalid sessions: 5 (3 female, 2 male)
	Left hand	• Sessions: 5 • Valid sessions: 2 (1 female, 1 male) • Invalid sessions: 3 (2 female, 1 male)

4.2.2 Forefeet and heels

Forefeet and heels of participants with normal hearing were tested (see Table 4.4). Participants were all right-handed and carried out the experiment using the right foot. Valid data was collected from 29 participants (15 female and 14 male). The age of these participants was in the range 17 to 57 years ($M = 31.7, \sigma = 11.4$); the age of 4 participants was between 50 and 57 years, 2 participants were aged between 41 and 49 years, 6 participants were aged between 30 and 39 years and the remaining 17 participants were aged between 17 and 29 years, their foot size (UK system) was in the range 4 to 15.5 ($M = 7.2, \sigma = 2.6$); their weight in the range 42 to 125kg ($M = 66.3, \sigma = 16.5$); and their height was in the range 1.5 to 2m ($M = 1.65, \sigma = 0.1$). Note that the proportion of valid sessions performed with forefeet (87%) and heels (100%) was considerably larger than the proportion of valid sessions performed with fingertips (78%). This is discussed later in this chapter.

There were 15 participants tested without payment, 14 participants were paid £10 per test session and 1 participant was paid for their travel expenses.

Table 4.4 Sessions to measure detection thresholds using the right foot of participants with normal hearing.

<table>
<tr><td rowspan="2">• No. of participants: 30

• No. of sessions: 43
• Valid sessions: 40
• Invalid sessions: 3</td><td>Forefeet</td><td>• Sessions: 23
• Valid sessions: 20 (10 female, 10 male)
• Invalid sessions: 3 (2 female, 1 male)</td></tr>
<tr><td>Heel</td><td>• Sessions: 20
• Valid sessions: 20 (10 female, 10 male)
• Invalid sessions: 0</td></tr>
</table>

4.3 PROCEDURE

This section explains the procedure to perform subjective measurements and complements the description of the procedures explained in Sections 3.2.1.1 and 3.3.1.1 to perform objective measurements using both the set-up for the fingertips in the audiometric booth and the set-up for the forefeet and heels in the semi-anechoic chamber.

4.3.1 Fingertips

4.3.1.1 Objective measurements

The calibration procedure was based on the reference levels for the test tones shown in Table 3.1 (see Section 3.2.1.1.A). The reference levels were checked before and after each experimental session in order to ensure that they remained stable within a tolerance of approximately ±0.5dBVrms. This ensured accurate subjective measurements according to the procedure to obtain acceleration values explained in Section 3.2.1.1.B.

4.3.1.2 Subjective measurements

A. Detection thresholds

The test procedure to determine vibrotactile detection thresholds was adapted from the standard audiometric test method that determines thresholds using pure-tone air conduction and is known as the shortened version of the ascending method [155]. According to the Standard ISO 13091-1[103] and Levitt [100], the method was a staircase algorithm with the sequence of stimuli increasing and decreasing using equal-sized steps as described below.

According to [103], vibrotactile thresholds are determined using a probe or contactor of small area and a fixed rigid surface with a hole that surrounds the contactor in order to limit the propagation of skin surface waves beyond the perimeter of the contactor surround. However, a singer or musician needs a contactor area that is sufficiently large to be used during performance. Alternatively, musicians may also want to monitor the vibration on the surface of their musical instrument. For these reasons, a contactor surround was not used in the present experiment.

Commercial implementations of vibrometers [109] tend to measure the applied force and compensate for this or indicate to the user when the force is appropriate. This was not carried out in this research because it would not be feasible for a singer or musician to monitor and modify their applied force during performance.

In audiometry, the starting tone is chosen as 1kHz which is in the frequency range of highest sensitivity for the human ear. Similarly, to determine vibrotactile thresholds the test tone C4 (261.6Hz) was chosen because it approximately corresponded to the frequency of highest sensitivity for the Pacinian corpuscle [108, 110]. The order of presentation of test tones began with C4 ascending up to C6 (1046.5Hz), followed by tones descending from G3 (196Hz) to C1 (32.7Hz). Thus, a series of eleven test tones were presented.

The stimulus consisted of a sequence of one-second tone bursts that were presented three times in a row, with each tone burst separated by a two-second pause such that the total length of the sequence was seven seconds. The audiometric procedure uses a discrete step rate of 5dB HL, where dB HL (hearing level) indicates the units used in Europe to specify detection thresholds of a sound relative to the average threshold measured on healthy listeners with "normal" hearing [160]. However, the procedure to measure vibrotactile thresholds used a smaller step rate of 2dBV.

Participants were instructed as follows: (1) to place the middle part of the fingerprint of the middle finger of their dominant hand on the contactor disc; (2) to relax their arm and not to press down upon the contactor; and (3) to use their free hand in order to press the response button provided whenever they felt a tone in the stimulus sequence. At least two out of the three tone bursts in the stimulus sequence had to be felt by the participant for the response to be regarded as elicited. The complete script for participants is provided in Section B.1.5 of Appendix B. For each run of a test tone, the following stages were followed:

Familiarisation stage: (a) The stimulus for tone C4 was presented at a reference level which could be felt by all participants; (b) the stimulus level was then decreased in steps of 20dBV until no response was elicited; (c) the stimulus level then ascended in steps of 2dBV until a response was elicited; (d) the stimulus was then presented again at reference level.

Stage 1: The stimulus was presented 10dBV below the level of the participant's response elicited during the familiarisation stage. Then the stimulus level ascended in steps of 2dBV until a response was elicited.

Stage 2: The stimulus was presented 10dBV below the level of the participant's response elicited during stage 1 and then another ascent was started. The procedure continued until either (a) a final outcome of two responses elicited at the same level, out of a maximum of three ascents, was reached (excluding the familiarisation stage) or (b) three ascent responses represented three consecutive steps in level, in which case the median was regarded as the elicited response. Otherwise, the stimulus for the tone started from the familiarisation stage until condition (a) or (b) was satisfied.

After stage 2, the stimulus for the next test tone was presented starting from the familiarisation stage through to stage 2 again. Once the entire set of eleven test tones had been presented, the below verification stage was carried out.

Verification stage: The stepwise presentation of the stimulus for tone C4 was repeated from the familiarisation stage through to stage 2. If the outcome on this occasion was within ±4dBV of the outcome of the initial stimulus for tone C4 and the skin temperature on the fingertip was within the acceptable range, the results for the entire set of the eleven test tones was deemed valid. Based on the findings of Verrillo and Bolanowski [83], the acceptable (and practically achievable) temperature ranges were chosen to be 20 to 36ºC for test tones C1 (32.7Hz) to G2 (98Hz) and 24 to 36ºC for test tones C3 (130.8Hz) to C6 (1046.5Hz). The temperature on the fingertip was monitored at approximately 20-minute intervals. The temperature in the room was maintained in the range 19 to 31ºC.

A complete test session for each participant lasted approximately 1.5 hours. This included approximately 15 minutes to brief the participant before starting the test procedure and two or three rest periods. Each rest period lasted approximately five minutes after approximately 20 minutes of testing.

The procedure was programmed in Matlab as a graphical user interface (GUI) that was controlled by the experimenter and provided an automatic presentation of the stimuli to the participants. A flowchart representing the procedure along with figures of the GUI is shown in Section B.2.1 of Appendix B. In addition, the GUI program simplified the data collection by outputting the results in terms of acceleration at the end of the test session. An example of the output file for these results is provided in Section B.2.2 of Appendix B.

B. Occlusion effect

In order to dissociate the vibrotactile sensation from both pure-tone air and bone conduction, masking noise was used to avoid any air conduction of high sound levels radiated by the shaker and contactor disc (see Section 3.2.1.1.C). This approach was also used by Verrillo and Capraro [157], who concluded that audible airborne sound from the shaker can significantly affect the measured threshold.

Due to the potential conduction of sound to the inner ear of the participant through their cranial and other bones, the occlusion effect was investigated. According to standard audiometric methods [155], this effect produces a change in the level of a bone-conducted tone when the entrance to the ear canal is occluded with earphones or by other means. The effect is due to the enclosed air volume formed in the external ear, which affects the perception of tones particularly below 1kHz.

In order to determine whether the occlusion of the ear canal could affect the measurements of detection thresholds on the fingertips, e.g. by wearing hearing aids during a test session, a variation of the experiment was performed wearing first earplugs and then hearing defenders.

C. Transient and continuous parts of test tones

The final variation of the experiment was performed in order to investigate the perception of test tones regarding the transient parts at the beginning and end of the test tones, and the continuous part in the middle. This can be described in relation to the typical amplitude envelope of a musical note which has four sequential stages: attack (i.e. transient part), decay, sustain (i.e. continuous part) and release (i.e. transient part) [150].

During the threshold measurements, some participants commented that there were distinct differences in perceiving the onset and sustain of high-pitched tones compared to low-pitched tones. The same sensation was reported by von Békésy [161], who used electrodes and mechanical vibration to stimulate the fingertip, as follows: “Especially during the onset or offset of the ac stimulus, a small push or pull is discriminated, which increases in magnitude with increasing frequency.” In fact, five out of the thirty-two participants tested on the right hand were not able to feel the tone C6. Exploring further this temporal aspect of pitch perception was useful in order to define a practical and safe vibrotactile dynamic range.

Fourteen participants repeated the experiment to measure detection thresholds for eleven test tones ranging from G4 (392Hz) to C6 (1046.5Hz) corresponding to white notes in a piano keyboard. Once the threshold had been determined for a tone, the participant was again presented with the stimulus sequence at threshold level and a two-alternative forced choice was used to ask (a) whether they felt transient vibration at the beginning and/or end of any of the one-second tones in the sequence and (b) whether they felt continuous vibration during any of the one-second tones in the sequence. The same stimulus sequence was then presented at 10dBV above threshold and the questions were repeated before proceeding with the next tone. Figure B.4 in Section B.2.3 of Appendix B shows the GUI panel used to record the answers to these questions.

4.3.2 Forefeet and heels

4.3.2.1 Objective measurements

As with the objective measurements on fingertips, the calibration procedure was based on the reference levels for the test tones checked before and after each test session (see Section 3.3.1.1.A).

4.3.2.2 Subjective measurements

Apparatus and scripts to instruct participants in the measurements on the fingertip were modified in order to adapt them to the experimental set-up to measure on the foot. Participants were asked to remove their footwear and roll their trousers or dress up to the right knee in order to avoid any sensation from the clothes.

As explained in Section 3.3.1.1.F, the procedure to measure detection thresholds was effectively the same in the experimental set-ups for fingertips, forefeet and heels, except for the foot load compensation. For each test tone, the change of acceleration levels due to pressing lightly compared to without placing the foot on the disc was measured twice for each participant and for approximately two minutes each time: Once before starting the session of measurements of detection thresholds and once after finishing the session of measurements of detection thresholds. Participants were asked to keep their foot still and the presentation level was 10dBV below the reference levels in order to avoid any potential adaptation discussed later in this chapter.

The average obtained from each pair of measurements was used to correct some threshold values. An example of the threshold values measured for a participant before the compensation is shown in Section B.2.2 of Appendix B. The post-hoc compensation was applied on the threshold values for the tones that changed acceleration by 1dBVrms or more during the pre-and post session measurements (see Table A.3 in Appendix A). Thus, an individual correction was used to obtain acceleration values that accounted for the reduction in the acceleration.

4.4 RESULTS, ANALYSIS AND DISCUSSION

This section discusses the results from the measurements performed on fingertips, forefeet and heels of participants with normal hearing. A comparison of results from measurements performed on the fingertips of participants with hearing impairments is also discussed.

Analysis was performed using the SPSS software with either parametric (dependent and independent *t*-tests) or non-parametric (Mann-Whitney) tests. The assumptions for parametric data included (a) data measured at ratio level, (b) normality of distribution, and (c) homogeneity of variance if different groups of participants were to be compared. Normality was checked using the Shapiro-Wilk test because of its sensitivity, even with small-sized samples [162]. The conclusions for the tests were the same regardless of whether linear units or decibels were used.

4.4.1 Fingertips

This section contains the results for vibrotactile thresholds with fingertips including the repeatability of measurements and the occlusion effect for participants with and without hearing impairments. This provides the data to assess a practical and safe dynamic range that could be used for music performance or practice. It also contains the results and analysis of the perception of transient and continuous parts of test tones.

4.4.1.1 Occlusion effect

Figure 4.1 shows that the thresholds of three participants with normal hearing wearing hearing protectors or earplugs are not significantly different to the unoccluded test because these results fall within the error bars for the average of three repeat tests with ears unoccluded. This suggests that the thresholds for participants with normal hearing or with hearing impairments are unlikely to be affected by earplugs, hearing protectors or hearing aids occluding the ear canal.

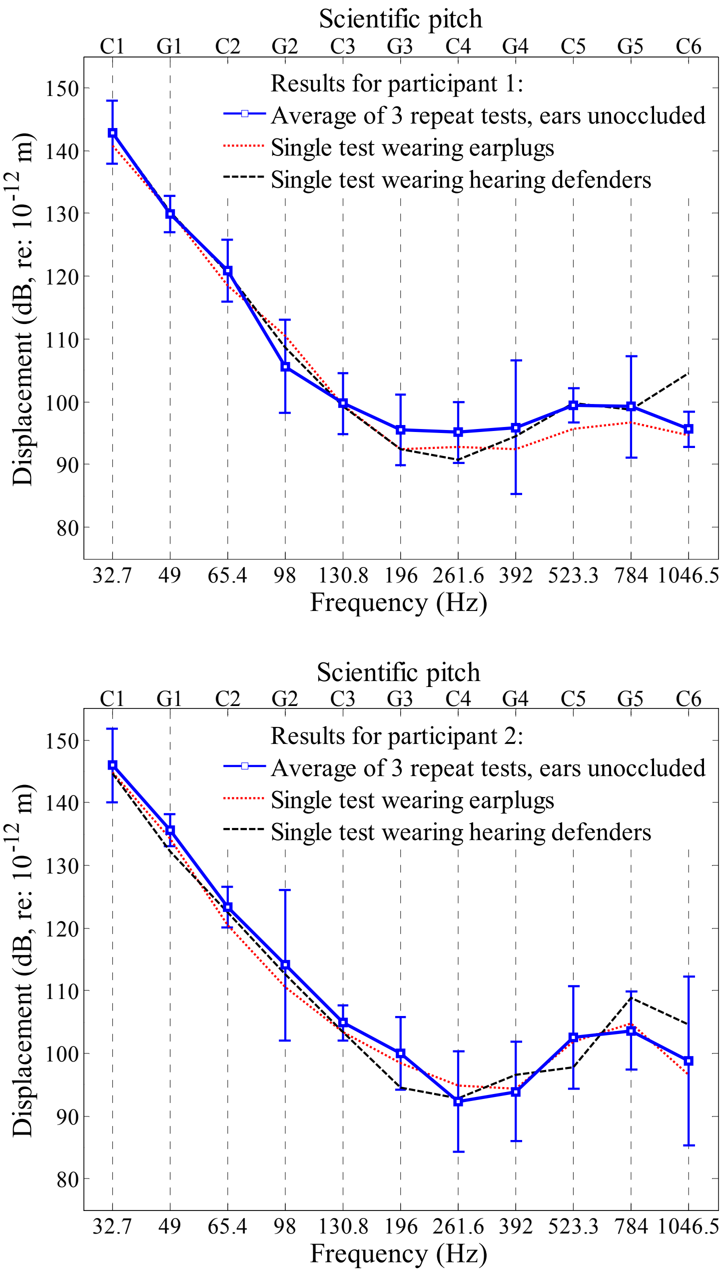

Figure 4.1 Results for the middle fingertip of three participants with normal hearing to test occlusion effect and results repeatability (error bar indicates one standard deviation). The figure continues on the next page.

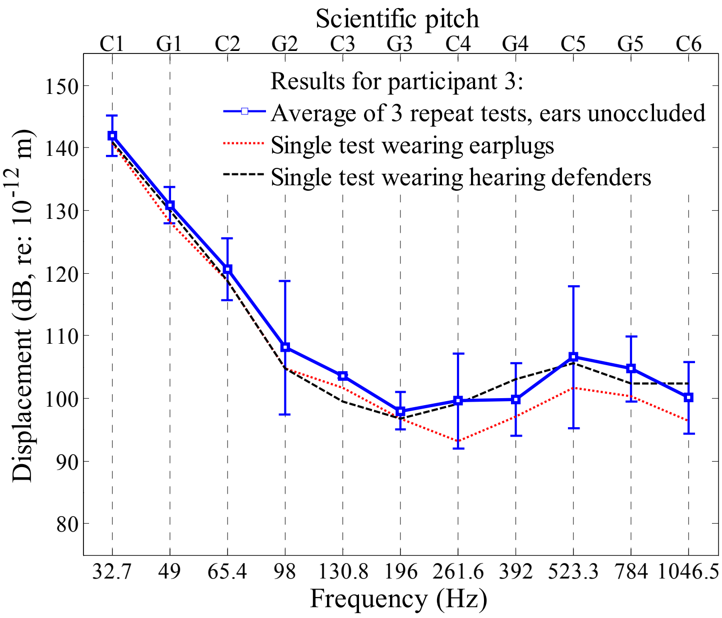

Figure 4.1 (continued) Results for the middle fingertip of three participants with normal hearing to test occlusion effect and results repeatability (error bar indicates one standard deviation).

4.4.1.2 Detection thresholds

Figure 4.2 shows that individual participants have markedly different thresholds. Similar differences in the variation of vibration thresholds for individual participants can be found in [32, 91, 111].

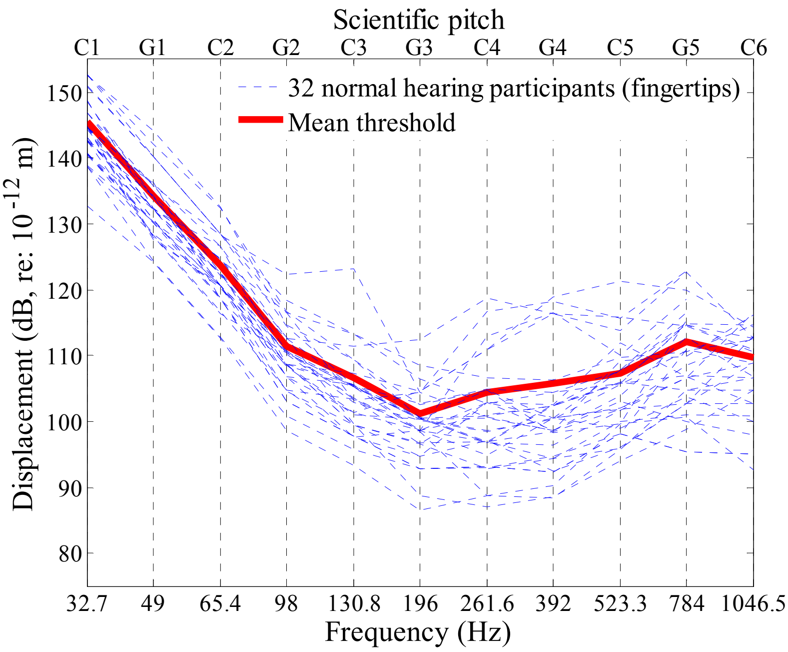

Figure 4.2 Detection thresholds on the middle fingertip of the right hand from 32 participants with normal hearing.

In line with these psychophysical studies in the literature, the mean threshold in Figure 4.2 was calculated using the arithmetic average of the root-mean-square displacement which shows the characteristic shape for the Pacinian corpuscle [108]. The lowest mean threshold occurs at G3 (196Hz) which is similar to findings from Morioka and Griffin [110] and Verrillo [108]. Similar differences in hearing thresholds for similar age and gender groups are also found in [163] where mean values are also used to specify detection thresholds, as indicated in [160] (see Section 4.3.1.2.A).

Figure 4.3 shows these vibrotactile threshold values using boxplots. Whiskers extend from the lowest to the highest value. The 25th and 75th percentiles of the values form the edges of each box that contains the middle 50% of the values. The median is the red line. Each whisker can extend up to 1.5 times the box length (the whisker marks represent all values within ±3 standard deviations from the mean [164]) and the circles represent outliers outside this range [165, 166]. The boxplots clarify the different ranges of sensitivity for each test tone as well as the symmetry of the distribution of the responses, the type of which was confirmed using the aforementioned assumptions for parametric data.

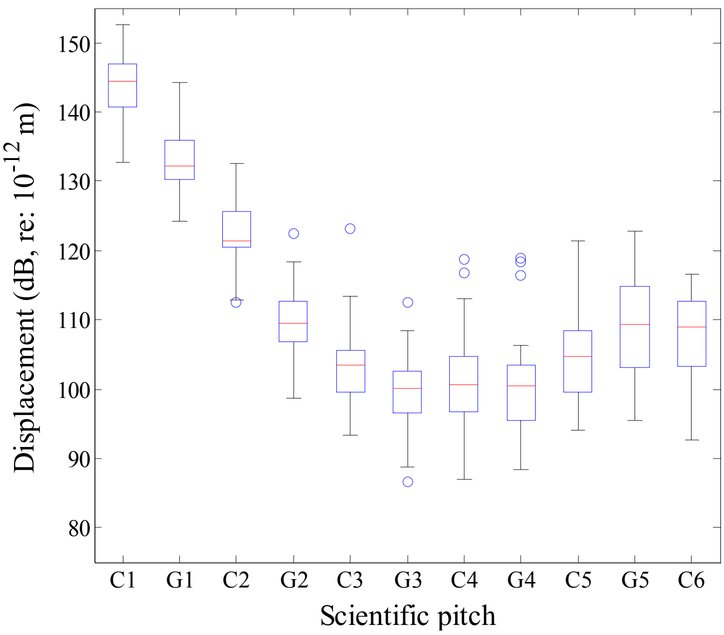

Figure 4.3 Boxplots for detection thresholds on the middle fingertip of the right hand from 32 participants with normal hearing.

The participants with outlier responses in Figure 4.3 were removed, a subset of 16 participants was randomly chosen and then an additional subset of 8 participants was also randomly chosen. The 95% confidence intervals in Figure 4.4 indicate that this reduction in the sample of participants does not produce a substantial change in the mean threshold. In the chosen subset of 16 participants, 1 participant was aged 65 years, 1 participant was aged 40 years, 3 participants were aged between 33 and 35 years and the remaining 11 participants were aged between 22 and 28 years. In the chosen subset of 8 participants, 1 participant was aged 40 years, 2 participants were aged between 33 and 35 years and the remaining 5 participants were aged between 24 and 28 years.

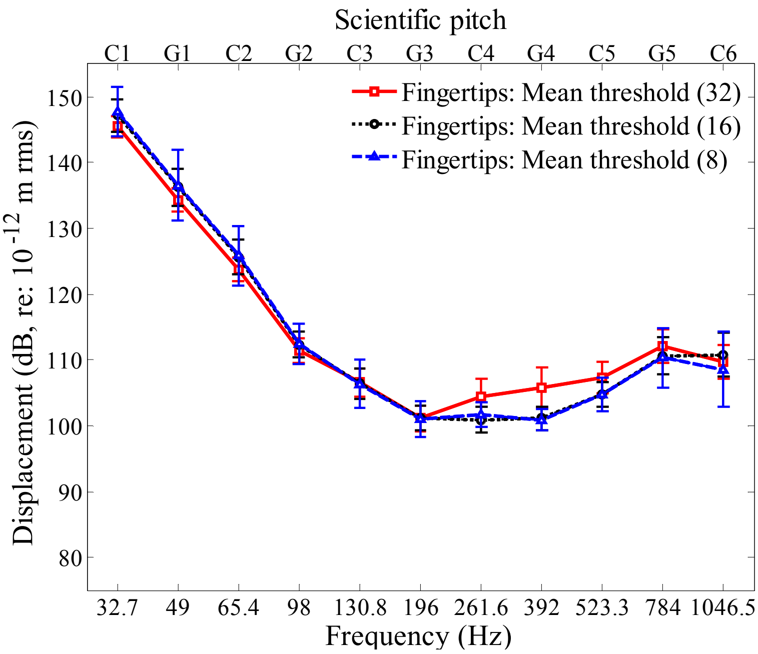

Figure 4.4 Detection thresholds on the middle fingertip of the right hand from 32 participants with normal hearing (cf. Figure 4.2) compared with subsets of 16 and 8 participants. The number of participants is indicated in brackets.

Table 4.5 shows no significant difference between the thresholds obtained with right and left hands (independent *t*-test, $p > 0.05$). This supports the findings of Verrillo and Bolanowski [23, 167] who tested the presence of contralateral differences in relation to hand preference and found no significant differences in detection sensitivity between right- and left-handed participants.

Table 4.5 Statistical results from the independent *t*-test used to compare thresholds measured on the middle fingertip of the right and left hands.

Note	p^a	$t(47)^b$	r^c
C1	0.521	−0.647	0.094
G1	0.965	0.044	0.006
C2	0.762	0.304	0.044
G2	0.754	−0.315	0.046
C3	0.882	0.150	0.022
G3	0.669	−0.430	0.063
C4	0.457	0.749	0.109
G4	0.849	−0.192	0.028
C5	0.811	−0.240	0.035
G5	0.833	0.212	0.031
C6	0.770	0.295	0.048

[a] Probability value. [b] Independent *t*-test statistic and degrees of freedom ($df = 38$ for note C6).
[c] Effect size.

Figure 4.5 shows the mean threshold expressed in terms of peak displacement for comparison with other psychophysical studies in the literature by Lamoré and Keemink [111], Goble *et al* [91], and Harada and Griffin [32]. The threshold from the present study is higher than the thresholds from these other studies which did not use a contactor surround and used different equipment and test procedures. Unfortunately, it is rarely possible to determine the standard deviation from other published studies; therefore, 95% confidence intervals can only be shown for the present experiment. Assuming that the confidence intervals in the other studies are similar, it would be reasonable to expect the confidence intervals from the present experiment to overlap with those reported by Harada and Griffin.

The main differences between the present experiment and these other studies are a different contactor area and, in some cases, different stimuli duration. The contactor area used by Harada and Griffin was 0.39cm^2, 1.4cm^2 by Goble *et al* and 1.5cm^2 by Lamoré and Keemink. These areas are notably smaller than the 3.14cm^2 contactor area used in the present experiment. The duration of the stimuli in the present experiment was 1s as in Lamoré and Keemink but longer than in Goble *et al* who used 0.5s; no duration is stated by Harada and Griffin. The present results can therefore be said to resemble prior findings, the differences being due to experimental equipment and measurement procedures. Further details about these experimental conditions and procedures are summarised by

Morioka and Griffin [110]. Similar differences were found in a similar comparison made by Bolanowski *et al* [21] for results obtained from hairy skin.

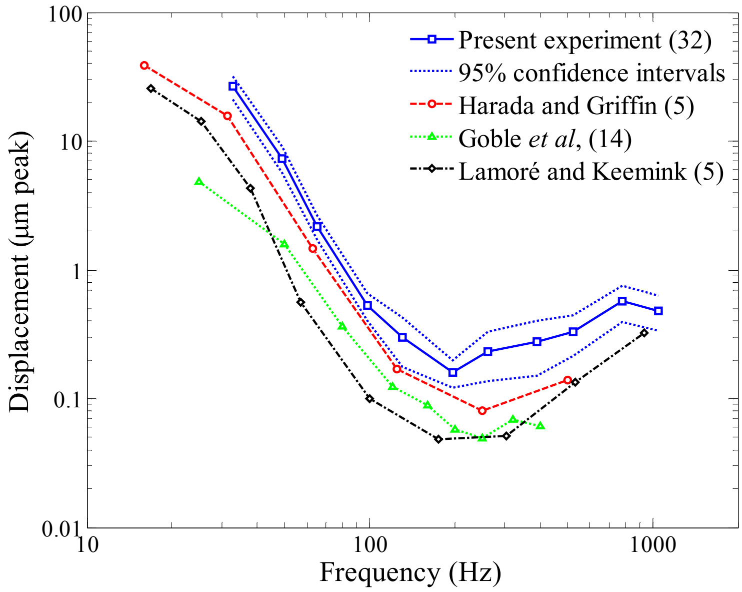

Figure 4.5 Comparison of detection thresholds measured on the middle fingertip from participants with normal hearing without using a contactor surround. The number of participants is indicated in brackets.

4.4.1.3 Detection thresholds for participants with hearing impairments

Thresholds of participants with hearing impairments fell within the range for participants with normal hearing that is defined by the shaded area in Figure 4.6.

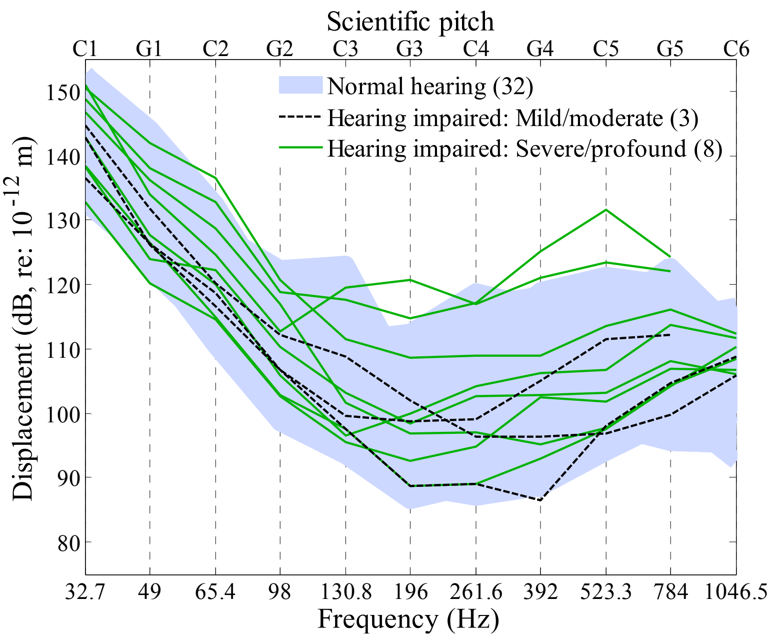

Figure 4.6 Comparison of detection thresholds measured on the middle fingertip of participants with normal hearing (grouped in the shaded area) and with hearing impairments. The number of participants is indicated in brackets.

In addition, Table 4.6 shows no significant difference between the thresholds for both groups of participants with normal hearing and with a severe or profound hearing impairment (Mann-Whitney, $p > 0.05$).

Table 4.6 Mann-Whitney test results to compare thresholds on the middle fingertip from participants with normal hearing and with a severe/profound hearing impairment.

Note[a]	p	U[b]	r
C1	0.813	121.000	−0.040
G1	0.499	108.000	−0.110
C2	0.588	112.000	−0.090
G2	0.612	113.000	−0.080
C3	0.813	121.000	−0.040
G3	0.919	125.000	−0.020
C4	0.398	103.000	−0.130
G4	0.105	80.000	−0.260
C5	0.499	108.000	−0.110
G5	0.327	99.000	−0.160
C6	1.000	81.000	0.000

[a] Observations, $N = 40$ except for C6 ($N = 33$). [b] Mann-Whitney test statistic.

4.4.1.4 Dynamic range

The measured vibrotactile thresholds are now used to establish a usable dynamic range for vibrotactile feedback on fingertips. This is necessary because it is imperative that musicians using vibrotactile feedback are aware of high levels of vibration that can cause adverse health effects in terms of vascular symptoms. The measured vibrotactile thresholds in Figure 4.2 were converted to frequency-weighted acceleration for comparison against an upper limit of 1ms^{-2} rms [103, 156]. Vascular symptoms would not usually occur below this value when considering normal usage of hand-tools [168]. According to [156], the frequency weighting factors were defined by the transfer function of the filter, $H_{\mathrm{w}}(s)$:

$$H_{\mathrm{w}}(s) = \frac{(s + 2\pi f_3)\, 2\pi K f_4^2}{\left(s^2 + \dfrac{2\pi f_4 s}{Q_2} + 4\pi^2 f_4^2\right) f_3} \tag{4.1}$$

where $s = \mathrm{j}2\pi f$ is the variable of the Laplace transform, f_3 and f_4 designate a resonance frequency of 15.9Hz, $Q_2 = 0.64$ is the given selectivity and K is a constant gain. The transfer function of the frequency weighting filter is shown in Figure 4.7. The resulting frequency-weighted accelerations are shown in Figure

4.8 and indicate that the available dynamic range varied between approximately 8 and 37dB across the range of the required test tones (see Table 4.7).

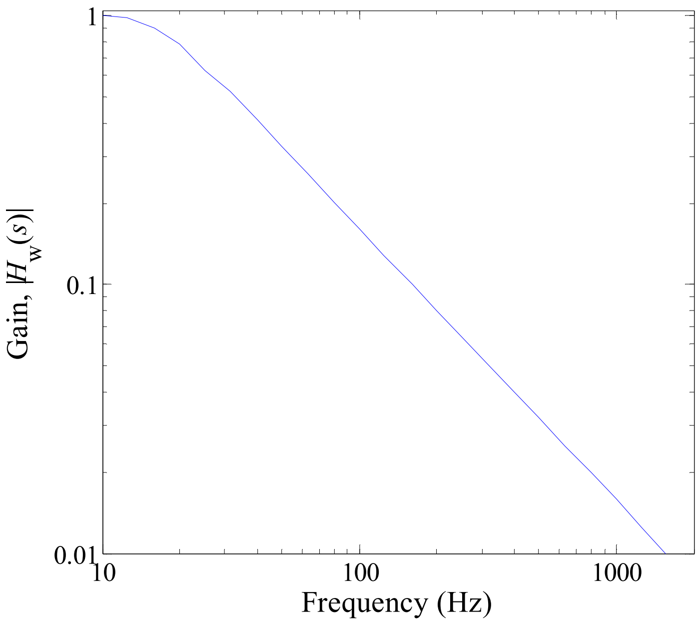

Figure 4.7 Transfer function magnitude (Gain) of frequency weighting filter.

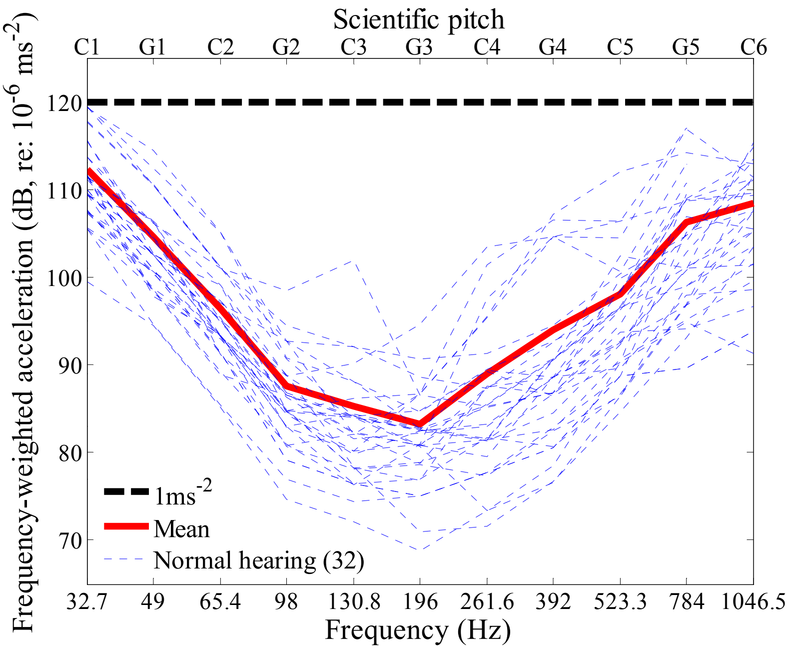

Figure 4.8 Detection thresholds in terms of frequency-weighted acceleration for the middle finger from the right hand of 32 participants with normal hearing for comparison with an upper limit of 1ms^{-2} (120dB).

Table 4.7 Dynamic range in terms of frequency-weighted acceleration.

Note	C1	G1	C2	G2	C3	G3	C4	G4	C5	G5	C6
Level, dB (re: $10^{-6}\,ms^{-2}$)	7.75	15.38	23.62	32.46	34.67	36.72	31.03	26.04	21.99	13.72	11.61

As expected, the available dynamic range for vibrotactile presentation of music is more limited than in the auditory mode. These results suggest that playing music using vibrotactile signals at threshold level would require excessive concentration, especially in the presence of significant background vibration.

Therefore, music signals would need to be presented at least 10dB above threshold. Consequently, the dynamic range for G1 (49Hz), G5 (784Hz) and C6 (1046.5Hz) would be less or equal than 5dB and the use of C1 (32.7Hz) would be quite limited. The effective dynamic range would vary between approximately 12 and 27dB over the three-octave range from C2 (65.4Hz) to C5 (523.3Hz).

4.4.1.5 Transient and continuous parts of test tones

When testing the perception of transient and continuous parts of test tones, the vibrotactile thresholds shown in Figure 4.9 indicate that the thresholds are approximately flat from G4 (392Hz) to C6 (1046.5Hz).

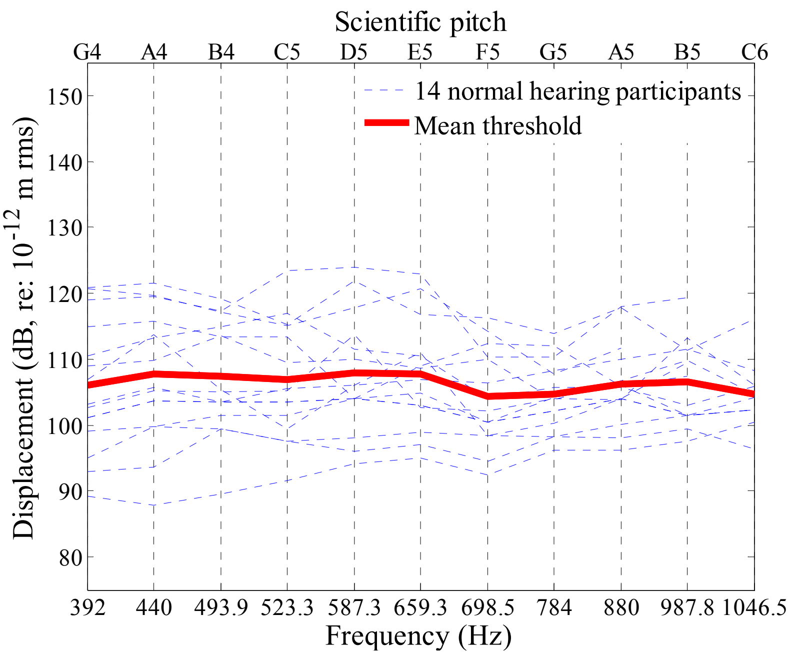

Figure 4.9 Detection thresholds measured on the middle fingertip of 14 participants with normal hearing and for the white notes between G4 and C6.

Figure 4.10 shows that participants' awareness of the transient parts of test tones increased with increasing pitch height, peaking at A5 (880Hz) and B5 (987.8Hz). Conversely, participants' awareness of the continuous parts of the tones was relatively high for the lower pitches in the range, decreasing at A5 and B5 where transient awareness peaked. Participants were typically more aware of the transient parts of each tone when presented 10dB above threshold compared to at threshold.

For tones between G4 (392Hz) and G5 (784Hz), on average 93.7% of participants responded positively that they could feel continuous vibration when presented with the stimuli at 10dB above threshold. However, when the tones were presented at threshold level, four out of the fourteen participants were not able to feel C6 (1046.5Hz) and one participant was not able to feel B5 (987.8Hz). This finding confirms the importance of presenting signals to musicians above threshold levels so that they are able to feel the continuous signal and assess pitch without having to concentrate on sensations close to, or at threshold level.

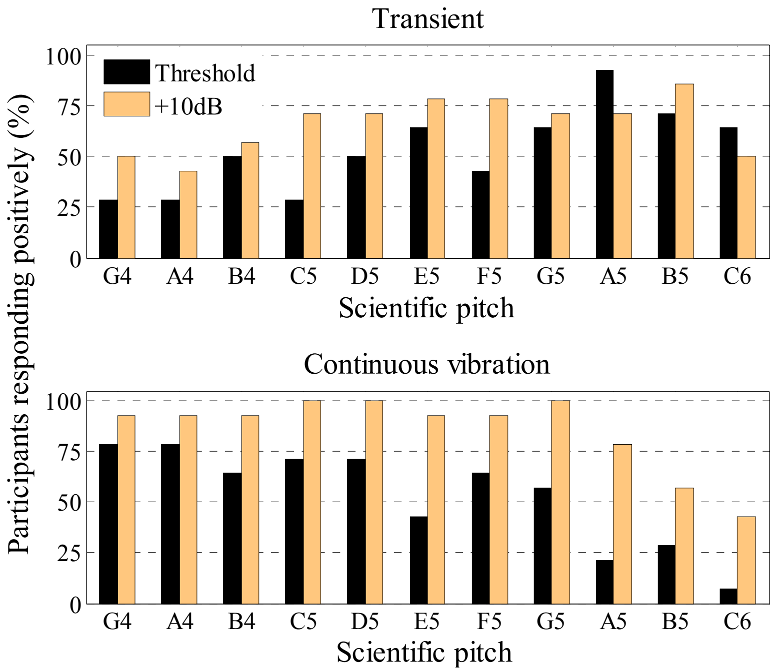

Figure 4.10 Percentage of 14 participants with normal hearing responding positively that the transient vibration at the beginning or end of the tone could be felt (upper graph) and that the continuous vibration of the tone could be felt (lower graph) via the middle fingertip.

For tones A5 (880Hz) to C6 (1046.5Hz) this reduction in the awareness of the continuous parts of the notes has implications for the vibrotactile perception of musical pitch because detecting only the onset of a musical note will not give sufficient information to identify the note itself, as discussed later in this chapter.

4.4.2 Forefeet and heel

As with results from fingertips, there is a large variation in the individual detection thresholds on forefeet and heels (see Figures 4.11 and 4.12). However, in contrast to the mean threshold from fingertips, the mean thresholds from forefeet and heels began to decrease above C5 (523.3Hz) which does not correspond to the characteristic shape for the Pacinian corpuscle. Similar variation for individual detection thresholds on the toe, ball of the foot and heel have also been shown using different experimental conditions that included a contactor surround and sinusoidal stimuli up to 250Hz in [109] and [169].

Note that two participants were not able to feel C6 (1046.5Hz) and one of them was not able to feel B5 (987.8Hz) using the forefeet when the test tones were presented at threshold level. Similarly, four participants were not able to feel C6 and one of them was not able to feel B5 using the heel.

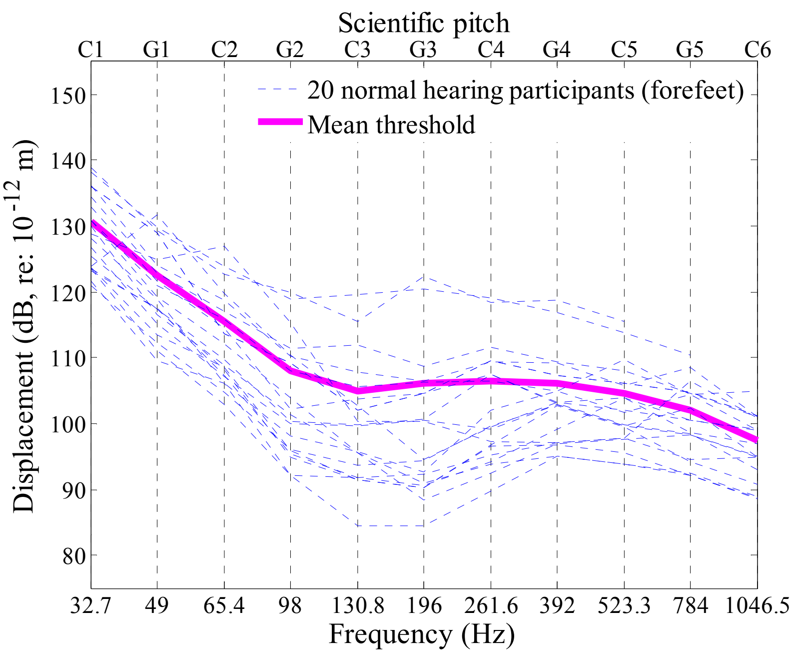

Figure 4.11 Detection thresholds on the forefoot from 20 participants with normal hearing.

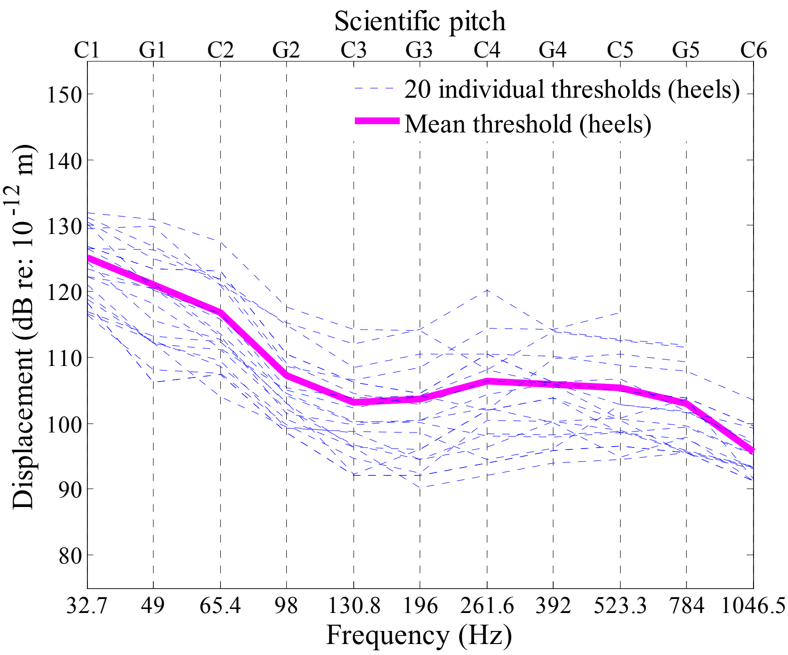

Figure 4.12 Detection thresholds on the heel from 20 participants with normal hearing.

Figure 4.13 and Table 4.8 show no significant difference between mean thresholds for heels and forefeet (independent *t*-test, $p > 0.05$), except for C1 which showed a large-sized effect, $r = 0.44$.

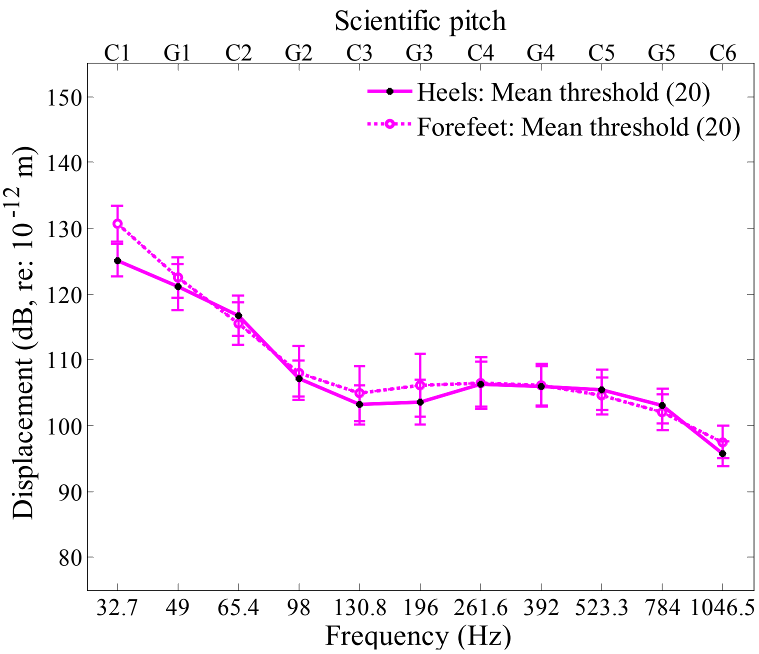

Figure 4.13 Mean detection thresholds on the forefoot and the heel from participants with normal hearing. The number of participants is indicated in brackets. The error bar indicates the 95% confidence interval.

Table 4.8 Statistical results from the independent *t*-test used to compare thresholds measured on the heel and the forefoot.

Note	*p*	$t(38)^a$	*r*
C1	**0.004**	3.053	**0.444**
G1	0.362	0.922	0.148
C2	0.442	−0.777	0.125
G2	0.591	−0.542	0.088
C3	0.760	−0.308	0.050
G3	0.644	−0.466	0.075
C4	0.794	−0.262	0.042
G4	0.885	−0.145	0.024
C5	0.769	−0.296	0.048
G5	0.673	−0.425	0.071
C6	0.382	0.887	0.155

[a] Degrees of freedom, *df* = 36 for note G5 and *df* = 32 for C6.

Figure 4.14 shows the mean thresholds for forefeet and heels for comparison with thresholds obtained by Morioka and Griffin [170]. They considered the entire sole of the left foot placed on a wooden footrest of 300cm^2 using vertical vibration and a different psychophysical testing method to the one used in the present experiment. In the present experiment, the contact areas of discs for the forefoot and the heel were 113.1cm^2 and 78.5cm^2, respectively.

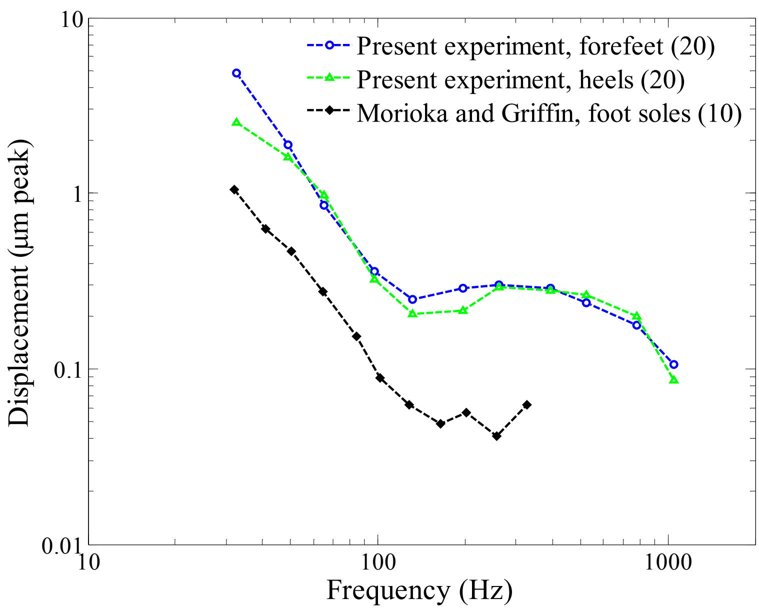

Figure 4.14 Results from forefeet and heels using the right foot of participants with normal hearing tested in the present experiment and using the entire sole of the left foot. The number of participants is indicated in brackets.

The differences in Figure 4.14 may be due partly to different experimental equipment and measurement procedures (cf. Figure 4.5 in Section 4.4.1.2). Nevertheless, the results in Figure 4.14 indicate that the threshold would be proportional to the contact area. Lower thresholds may be also due to spatial summation, i.e. the integration of energy over the contact area. Spatial summation was probably due to the lack of contactor surround, which caused the thresholds mediated by the Pacinian channel to be lower with larger contactor areas [23, 110, 170].

4.4.3 Comparison of results obtained from fingertips and feet

For the specific contact areas used in this experiment, Figure 4.15 and Table 4.9 show that the forefoot had significantly lower thresholds than the fingertips between C1 and C3 and for G5 and C6 (Mann-Whitney, $p < 0.05$). However, there was no significant difference between thresholds of fingertips and forefeet (Mann-Whitney test, $p > 0.05$) in the range G3 to C5.

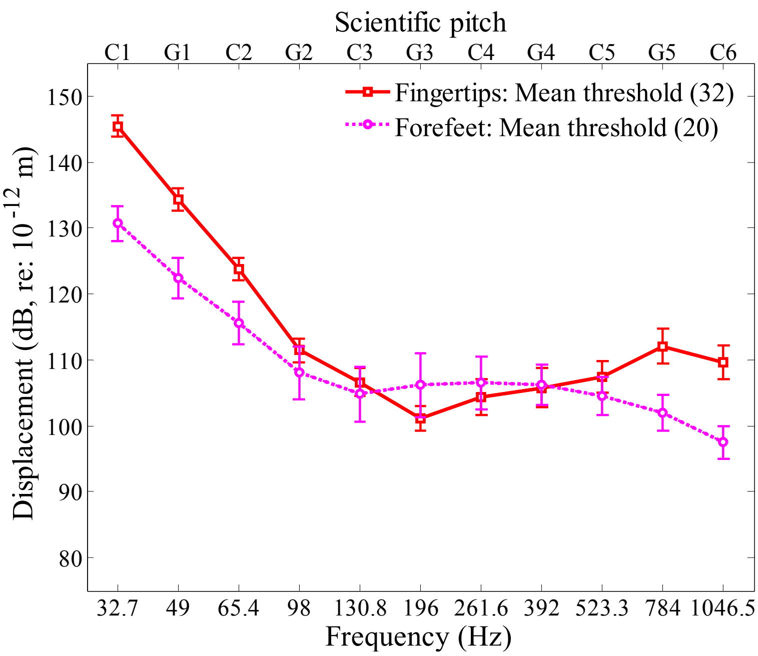

Figure 4.15 Mean detection thresholds on the fingertip from 32 participants with normal hearing and on the forefoot from 20 participants with normal hearing. The error bar indicates the 95% confidence interval.

Table 4.9 Statistical results from the Mann-Whitney test to compare thresholds for the middle fingertip and the forefoot.

Note[a]	p	U	r
C1	**0.000**	9.000	**−0.810**
G1	**0.000**	35.000	**−0.740**
C2	**0.000**	90.000	**−0.600**
G2	**0.008**	179.000	**−0.370**
C3	**0.044**	213.000	**−0.280**
G3	0.612	293.000	−0.070
C4	0.679	298.000	−0.060
G4	0.114	236.000	−0.220
C5	0.176	248.000	−0.190
G5	**0.000**	94.000	**−0.570**
C6	**0.000**	45.000	**−0.680**

[a] Observations, $N = 52$ except for note G5 ($N = 51$) and C6 ($N = 45$).

Figure 4.16 and Table 4.10 show a significant difference between the mean thresholds for fingertips and heels (independent t-test, $p < 0.05$), except between C3 and C5.

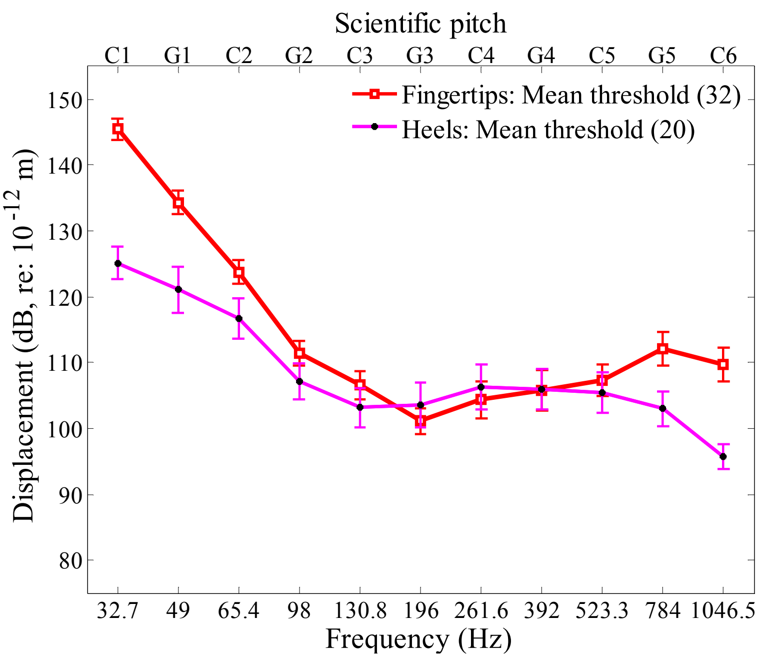

Figure 4.16 Mean detection thresholds on the middle fingertip from 32 participants with normal hearing and on the heels from 20 participants with normal hearing. The error bar indicates the 95% confidence interval.

Table 4.10 Statistical results from the independent *t*-test to compare the thresholds for the middle fingertip and the heel.

Note	*p*	$t(50)$[a]	*r*
C1	**0.000**	14.892	**0.903**
G1	**0.000**	8.664	**0.775**
C2	**0.000**	5.129	**0.587**
G2	**0.003**	3.178	**0.410**
C3	0.063	1.900	0.259
G3	0.586	−0.549	0.077
C4	0.308	−1.029	0.144
G4	0.283	−1.085	0.152
C5	0.332	0.979	0.137
G5	**0.000**	4.270	**0.521**
C6	**0.000**	7.265	**0.750**

[a] Degrees of freedom, $df = 49$ for note G5 and $df = 41$ for C6.

4.5 IMPLICATIONS FOR MUSICAL PERFORMANCE

The contactors used in the present experiment had satisfactory frequency response and vibration uniformity and the equipment has potential to aid development of vibrotactile music technology (see Chapter 3). The area for the contactor for fingertips was 3.14cm^2, which was sufficiently large that it could be easily used by a singer or incorporated on a musical instrument. This approach overcomes some limitations of equipment developed by others.

Birnbaum and Wanderley [171] created a feedback system with small-sized contactors incorporated inside the open tone holes of a flute, which had the effect of the contactor surround affecting the perception of vibrotactile levels. Overholt *et al* [172] incorporated a tactile sound transducer on a violin and other feedback systems produced by McDonald *et al* [173], Hayes [129] and Holland *et al* [174] incorporate small vibrating motors that can reproduce only a small number of frequencies. However, a newer version of the Haptic Drum Kit [174] modified by Bouwer *et al* [175] incorporates tactors that have limited bandwidth with optimal response in the vicinity of 250Hz, i.e. the maximum sensitivity of the Pacinian corpuscle [176]. Perhaps, it should be born in mind that most of the Pacinian corpuscles are in the fingers and toes [73] and because percussionists normally use both hands and feet the vibrotactile perception of pitch would still be limited.

Section 4.4.1.1 showed that the occlusion of the ear canal does not significantly affect detection thresholds on the fingertip; hence there are no issues for those who perform music wearing headphones or hearing aids.

Compared with the proportion of valid test sessions using forefeet and heels, the proportion of valid test sessions using fingertips was 9% and 22% lower, respectively (see Sections 4.2.1, 4.2.2 and 4.3.1.2.A). This considerable lower proportion of valid test sessions using fingertips could be due to sensory adaptation and the associated decrease in sensitivity after prolonged vibrotactile stimulation [22, 84]. This could be also explained in conjunction with the different distribution of densities and response characteristics of Pacinian corpuscles on the sole of the foot and the fingertip, which remains unclear to date [74].

As suggested by Berglund and Berglund [84], a short recovery period that lasted up to three or four minutes was provided to a small sample of participants after their verification stage was not valid during the tests with fingertips. The verification was then repeated, but the results were similar to the first verification. It is possible that this short recovery time was not long enough or, as indicated by Gescheider and Wright [86], a neurological component may exist that hinders recovery. According to Lundström and Johansson [177], a prolonged and intense vibrotactile exposure of the fingertips to frequencies up to 400Hz may cause an increased tactile threshold and a decrease in the perception of intensity at suprathreshold level, which would also happen during musical performance. This change in perceived intensity may happen because the Pacinian and non-Pacinian channels seem affected by the exposure to test tones above and below approximately 50Hz, respectively, which is an overlapping region between both channels.

The forefeet and the heel were less prone to adaption than the fingertips, possibly due to a different capacity of the vibrotactile channels on these locations [73, 75] and, perhaps, the spatial summation which caused the thresholds mediated by the Pacinian channel to be lower with larger areas of stimulation [110, 170]. This happened despite the fact that these locations were equally sensitive in the domain of the Pacinian corpuscles and for the specific contact areas used in this experiment (Section 4.4.3).

It is possible that a lower density of Pacinian corpuscles on forefeet may enable musicians to have similar sensitivity than fingertips and a smaller tendency to adaptation in the vicinity of C4. This would be advantageous for musicians that would have their feet on a vibrotactile footrest for a long time while using their hands to play an instrument. In addition, Morioka and Griffin [170] found that thresholds measured on the sole of the foot are not greatly affected by wearing shoes or participant gender for frequencies up to 315Hz.

Section 4.4.1.3 concluded that there was no significant difference between participants with normal hearing and with profound or severe hearing impairments. The findings from the present experiment can then be interpreted regardless of the participants' hearing ability. This is a positive outcome because musicians from both groups could benefit from vibrotactile feedback. Moallem *et al* [95] compared the mean thresholds of detection of vibrotactile sinusoidal stimuli at 2, 5, 10, 25, 50, 100, 200, 250 and 300Hz using the fingertip of the index finger between fourteen participants with normal hearing and nine profoundly deaf participants and did not find a significant difference between the thresholds of both groups of participants at any frequency tested. Similarly, Bernstein *et al* [96] tested thirty-six participants with normal hearing and two profoundly deaf children who were found at least as sensitive to the tactile stimulation as the hearing participants.

Nanayakkara *et al* [178] used a haptic chair to present vibrotactile music simultaneously at the fingertips, hands, feet and the back of 43 participants who were partially or profoundly deaf. The results showed no significant difference between these two groups in the level of enjoyment of the musical experience.

Due to the individual variability in the detection thresholds and the unpleasantness from high vibration levels, Merchel *et al* [179] suggested that a usable dynamic range would have to be smaller than approximately 35dB (re: 10^{-6} ms^{-2}) for the equal contour magnitude levels reported by Verrillo *et al* [116]. Givens and Haas [180] suggested a similar dynamic range and claimed that speech sounds $\leq$ 1kHz could be used effectively as vibrotactile stimuli. According to the Standard on measurement of human exposure to hand-transmitted vibration [156], Altinsoy [181] and Abercrombie and Braasch [182] considered the effects of magnitude in sensitivity by weighting presentation stimuli up to 100Hz only in order to test the integration of both auditory and vibrotactile sensations. This consideration of human sensitivity is similar to the weighting of audio signals.

As shown in Section 4.4.1.4, the suggested safe limit of $1ms^{-2}$ (i.e. 120dB, re: $10^{-6}\,ms^{-2}$) in terms of frequency-weighted acceleration should be observed within the available dynamic range during prolonged vibrotactile stimulation on the fingertips in order to prevent adverse effects. Using a practical level at least ≈10dB above threshold, a dynamic range is expected to be approximately 12 to 27dB in the three-octave range C2 (65.4Hz) to C5 (523.3Hz). This substantiates the findings of Abercrombie and Braasch [182] who suggested that a listener walking across a single floor slab could perceive differences up to 26dB in terms of frequency-weighted acceleration measured with individual impulsive stimuli between 10 and 100Hz.

In addition, the forefoot and the heel would benefit from a slightly larger dynamic range for higher notes between approximately G4 (392Hz) and C6 (1046.5Hz) (see Section 4.4.2). In light of the results from the present experiment, it can be concluded that feet would be better at detecting high frequency notes but with a limited dynamic range in that frequency region.

The frequency weighting is based on equivalent comfort contours and detection threshold contours [183] and, according to Morioka and Griffin [184], a constraint is that the frequency weighting to be applied on thresholds for the foot is currently limited up to 315Hz and there have been discrepancies between British standards and international standards for these frequency weightings which are not consistent with detection thresholds. Therefore, unweighted acceleration has been suggested instead. Morioka and Griffin [170] have indicated that little or no investigation has been made on vibration levels that may affect the frequency-dependence of discomfort on the foot, concluding that “the magnitude-dependence of the equivalent comfort contours implies that no single linear frequency weighting can provide accurate predictions of discomfort caused by vibration of the foot”.

Consequently, different types of music would be appropriate to use in a vibrotactile set-up provided that the dynamic range is kept approximately within the aforementioned limits. Larger dynamic ranges may still be appropriate by compressing the dynamics of the signal avoiding distortion and improving reproduction quality [35]. Some examples for usual audio dynamic ranges produced by singers may vary approximately between 10 and 30dB for soprano, alto, and tenor singers [185]. The sound produced by orchestral string, woodwind and brass instruments may vary approximately between 2 and 20dB for individual notes between C1 and C7 [186].

There are also similar implications for large sound levels that can damage the hearing system. However, the skin may suffer other damages similar to those caused from frequent and prolonged exposure to vibration stimuli using hand-held vibrating tools in industrial environments; a well-known disease is vibration-induced white finger (or Raynaud's phenomenon) [187, 188], which may also produce long-term alteration of nerve fibre activity to the skin [189].

Branje *et al* [190] and Karam *et al* [191] have produced a multimodal entertainment chair that enables users to feel vibrotactile stimuli in order to enhance audio material that may also be presented simultaneously in films or video. However, this design would prevent a seating musician from adopting an adequate posture and they might be affected by prolonged whole-body exposure to high vibration levels. Perhaps, a chair design could allow for a vibrotactile foot rest similar to that considered by Nanayakkara *et al* [178], which could incorporate the findings in this thesis.

The duration of test tones is also important to investigate temporal aspects of music such as tempo, rhythm and timbre. The effects of the integration of stimulus energy over time (i.e. temporal summation) and the influence this has on threshold detection should be considered [23]. In addition, Weisenberger [53] noted the potential of the skin to detect fine structure temporal features such as voice onset in the range of tens of milliseconds, which would have a favourable implication for the identification of sang notes or those produced by some musical instruments with relatively fast onsets including percussion, string [192] and wind [193] instruments.

As shown in Section 4.4.1.5, notes with a duration of 1s that were close to or within the highest octave tested, i.e. between G4 (392Hz) and C6 (1046.5Hz) were detected at threshold level independently of frequency. This indicates the importance of presenting signals at suprathreshold level so that musicians are able to assess pitch effectively. However, as with audio signals [194, 195], the reduction in the awareness of the continuous parts of high-pitched notes A5 (880Hz) to C6 (1046.5Hz) would make it difficult to identify notes in this range.

4.6 SUMMARY

This chapter concerned vibrotactile thresholds measured without a contactor surround for notes C and G that were 1s long in the five-octave range from C1 (32.7Hz) to C6 (1046.5Hz) via the pad of the distal phalanx of the middle finger, the sole of the foot at the forefoot area and, separately, at the heel area. The test procedure was adapted from standard audiometric test methods [155] using a frequency range wider than that commonly tested in the literature, which provided a wide variety of fundamental frequencies of musical instruments that can be used in practical situations.

The detection thresholds measured on the middle fingertip for participants with normal hearing showed that the most sensitive frequency was in the vicinity of G3 (196Hz). It was advantageous for participants with normal hearing and with a hearing impairment that the potential confounding effect of the ear canal occluded by wearing hearing aids or headphones was not likely to affect the measured thresholds. In addition, no significant difference (Mann-Whitney, $p > 0.05$) was found between the thresholds for participants with normal hearing and participants with a severe/profound hearing impairment.

To prevent adverse health effects during musical practice, the available dynamic range was identified using the frequency-weighted acceleration. This dynamic range varied between approximately 8 and 37dB across the range of the tones tested. Because notes would typically need to be played approximately 10dB above threshold, the practical dynamic range varied between approximately 12 and 27dB from C2 (65.4Hz) to C5 (523.3Hz). Larger dynamic ranges and frequency ranges up to approximately G5 (784Hz) can also be used by compressing the dynamics of the signal. In practice, the change in the measured thresholds due to sensory adaptation during prolonged periods of exposure to high vibration levels should also be considered.

The experiment using the fingertip on higher frequency notes indicated that there may be problems identifying pitch at and above A5 (880 Hz) because the continuous part of these notes is not always felt at threshold or 10dB above threshold.

For the specific contactors used, the detection thresholds on the forefoot and the heel were very similar except for C1 which showed a significant difference (independent *t*-test, $p < 0.05$). In addition, this finding would not be greatly affected by wearing shoes [170]. However, there was a significant difference between thresholds on the fingertip and the forefoot or the heel, except between G3 (196Hz) and C5 (523.3Hz) for the forefoot (Mann-Whitney, $p > 0.05$) and between C3 (130.8Hz) and C5 (523.3Hz) for the heel (independent *t*-test, $p > 0.05$). This range of maximum sensitivity was then used to control the intensity of the test stimuli in order to assess relative pitch discrimination in the next experiment.

5 RELATIVE PITCH DISCRIMINATION AND LEARNING

5.1 INTRODUCTION

Relative pitch discrimination describes the ability to distinguish one musical note as being higher or lower than another [196, 197]. This chapter explains the experiment designed to assess relative pitch discrimination and learning on fingertips and forefeet. The main sections include descriptions of the type of participants, objective and subjective measurement procedures for each test session, and results with analysis and discussion.

Based on the research questions in Section 1.2.2 of Chapter 1, the experiment had three aims: (1) to specify the extent to which participants with normal hearing can discriminate musical intervals in the range of notes from C3 (130.81Hz) to C5 (523.25Hz), (2) to investigate how relative pitch discrimination can be learned and improved with training, and (3) to investigate whether severe and profound hearing impairments affect relative pitch discrimination.

5.2 PARTICIPANTS

This section provides details about the volunteers that participated in the experiment to test fingertips and forefeet. The entire set of participants had no self-reported impairment of sensation in their hands or feet and approximately 90% of the participants played a musical instrument and/or sang in a choir or vocal group. These data and the age and gender of participants are detailed below. Results from individual participants were partly considered, although the samples of participants used in the analysis of experimental data were regarded independently of age, gender and cognitive or musical skills.

5.2.1 Fingertips

There were a total of 17 participants with normal hearing (13 male and 4 female). The age of the participants was in the range 18 to 50 years ($\text{mean:}\, M = 27.7, \text{standard deviation:}\, \sigma = 9.5$). Only 1 participant was aged 50 years; 3 participants were aged between 40 and 41 years and the remaining 13 participants were aged between 18 and 29 years. Participants were right-handed and carried out the experiment using the middle finger of the right hand. Approval for the experiment was given by the Research Ethics Committees of the University of Liverpool and the Royal Northern College of Music in Manchester.

In Liverpool, nine participants were internally recruited and tested in the Acoustics Research Unit with no payment. These participants played a musical instrument and/or sang in a choir or vocal group to an amateur ability, except two participants who had no musical skills.

Afterwards, the experimental set-up described in Section 3.2.2 was moved to Manchester in order to test eight participants with normal hearing who were recruited and tested by RNCM. These participants played a musical instrument to an academic or professional extent and were paid £6.50 for sessions lasting up to 30 minutes and £10 for sessions lasting up to 60 minutes.

In addition, there were a total of five participants with hearing impairments (three male who were profoundly deaf and two female, one profoundly deaf and one severely deaf). The age of participants was in the range 25 to 59 years ($M = 36.2, \sigma =$12.8). Only 1 participant was aged 59 years and 1 participant was aged 49 years; the remaining 4 participants were aged between 25 and 30 years. Four participants were right-handed and carried out the experiment using the middle finger of the right hand. One of the participants was left-handed and carried out the experiment using the middle finger of the left hand. The participants were recruited and tested in Manchester and played a musical instrument to an academic or professional extent, except one of the profoundly deaf participants who had no musical skills. The participants were paid at the same rate as participants with normal hearing.

5.2.2 Forefeet

There were a total of nine male participants with normal hearing who were tested on the forefoot using the equipment described in Section 3.3.2. Their age was in the range of 26 to 51 years ($M = 34, \sigma = 9.2$). Only 1 participant was aged 51 years, 2 participants were aged between 41 and 42 years and the remaining 6 participants were aged between 26 and 30 years. The participants' shoe size for the system used in the UK was in the range 7.5 to 10 ($M = 8, \sigma = 0.8$), their weight was in the range 65 to 72kg ($M = 73.3, \sigma = 10.8$), and their height was in the range 1.69 to 1.85m ($M = 1.74, \sigma = 0.1$). Participants were all right-handed and carried out the experiment using the forefoot of the right foot.

Approval for the experiment was given by the Research Ethics Committee of the University of Liverpool. With the exception of one participant, all participants that previously carried out the test on the fingertips in Liverpool were recruited for the forefoot tests (also with no payment). As before, the participants played a musical instrument and/or sang in a choir or vocal group to an amateur ability, except two participants who had no musical skills.

5.3 PROCEDURE

The procedures to perform objective and subjective measurements on relative pitch discrimination were similar in the experimental set-ups for both the fingertip and the forefoot. However, the apparatus described in Sections 3.2.2 and 3.3.2 of Chapter 3, the graphical user interfaces and the scripts for participants were adapted from the set-up used for the fingertip to the set-up used for the forefoot.

5.3.1 Objective measurements

The presentation level of stimuli was based on the mean detection thresholds for fingertips and forefeet of participants with normal hearing (see Sections 4.4.1.2, 4.4.2 and 4.4.3 of Chapter 4). For the present experiment, the mean detection thresholds were chosen in the two-octave range of notes from C3 (130.81Hz) to C5 (523.25Hz) because this was the range of maximum sensitivity in the domain of the Pacinian corpuscle (the U-shaped portion of the mean threshold curve) [22]. In addition, the mean detection thresholds in that range were relatively flat and effectively the same for both fingertips and forefeet; the mean detection threshold averaged over the chosen range of notes was 0.187μm rms for fingertips and 0.193μm rms for forefeet. The average from these two thresholds corresponded to 105.5dB (re: 10^{-12} m).

A presentation level ≈15dB above threshold (i.e. 119.5dB, re: 10^{-12} m) was chosen because this was considered comfortable and easy to feel on fingertips and forefeet (see Figures 5.1 and 5.2). This presentation level also avoided exposing participants to high vibration levels over prolonged periods of time as indicated by British Standards [103, 156], Griffin [168] and as assessed in Section 4.4.1.4. Justification for this can be found in Cholewiak and Wollowitz [35]. They described variations in the human skin as a function of body site stating: “For 250 Hz vibrotactile stimuli on large (5 mm diameter) contactors, threshold amplitude may be as small as 0.2 µm on the finger or palm. […] (A common value for a ‘comfortable’ stimulus amplitude is 12-14 dB (4-5 times threshold), while ‘loud’ stimuli might be 20-40 dB above threshold.)”.

The presentation level also aimed to avoid effects of high vibration intensity affecting pitch perception, as reported by von Békésy [161] and Geldard [114]. Originally, von Békésy [115] investigated this issue and concluded: “[...] presenting the vibrations for only short time intervals [...] shows how the pitch sensation of a series of 100 pulses per sec changes on the finger tip as vibration amplitude increases. An increase in vibration amplitude of 50 db may produce a drop in pitch of as much as two octaves. Comparable changes were found on other parts of the skin”.

The resulting presentation level of stimuli at 15dB above threshold can also be justified from the experiments on subjective intensity carried out by Verrillo *et al* [116]. These established dynamic characteristics of vibrotactile stimulation with a family of curves representing the stimulus levels that were required to obtain a constant sensation on the palm of the hand in the frequency range 25 to 700Hz. They compared different psychophysical methods and found a remarkable similarity between the shapes of their equal sensation levels and those obtained for audition. Their resulting contours of equal sensation magnitude indicated that the shape of the contour does not substantially change when presented 15dB above threshold.

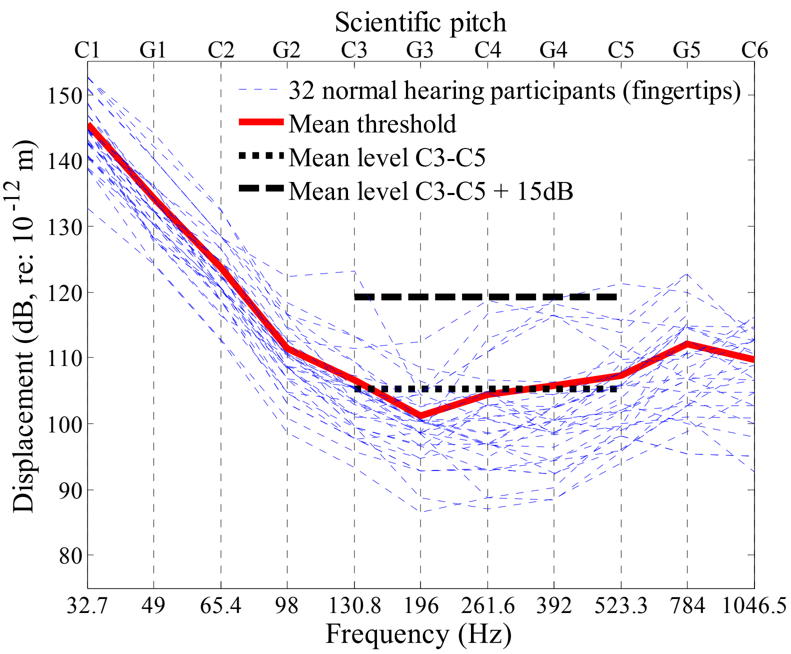

Figure 5.1 The mean detection threshold for the middle fingertip of the right hand from normal hearing participants was averaged over the range C3 to C5 and increased by 15dB to define the stimuli presentation level.

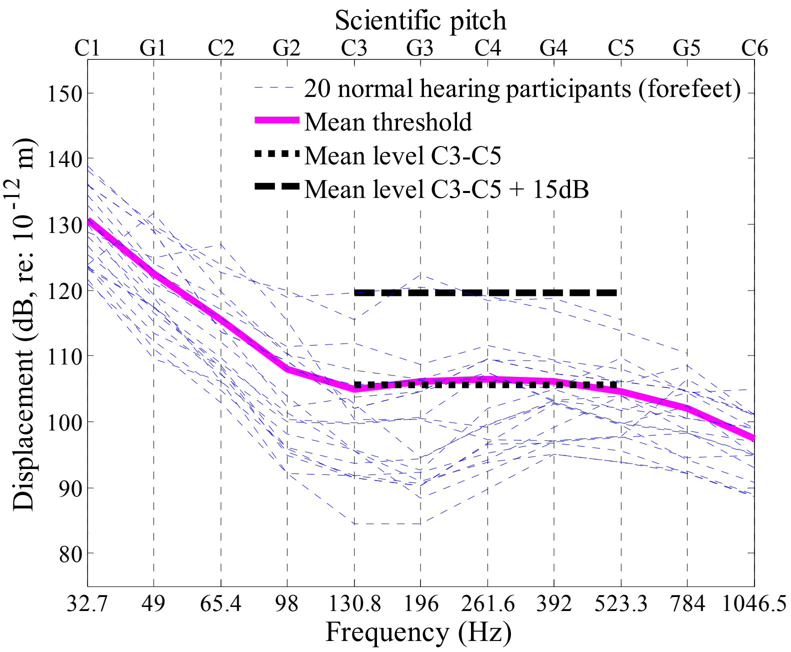

Figure 5.2 The mean detection threshold for the forefoot from normal hearing participants was averaged over the range C3 to C5 and increased by 15dB as the presentation level of stimuli.

The entire data set for stimuli at suprathreshold level is provided in Table C.1 of Appendix C. The reference values were measured regularly on the set-ups for fingertips and forefeet. This ensured that the measurements were stable throughout the subjective measurements.

In order to avoid unwanted audio cues caused by sound radiated by both shaker and contactor disc, broadband masking noise (white noise) was presented via headphones at a level of 75dB L_{Aeq} averaged for both ears (see Section 3.2.2). As described in Section 4.4.1.1, bone conduction due to any occlusion effect from wearing headphones did not affect vibrotactile perception.

5.3.2 Subjective measurements

Approval to perform the subjective measurements on both fingertips and forefeet was given by the Research Ethics Committee of the University of Liverpool. In both cases, the required documents and the scripts for participants were similar. The information sheet was adapted from the experiment on detection thresholds and the consent form and the questionnaire remained the same as in Appendix B, except for the title and the date information on the consent form (see Section B.1). The recruitment advertisement for this experiment is included in Section C.2 of Appendix C.

The procedure to perform the subjective measurements was designed with co-researchers in Manchester and involved three stages, namely comprehensive pre-training, training and a comprehensive post-training. As with previous studies on auditory pitch discrimination by Goff [117] and Cuddy [198], pairs of sinusoidal test tones were presented consecutively as stimuli during each stage of the experiment. Each tone in a pair lasted for 1s with an interval between them of 1s. After each pair of tones was presented, participants were asked ‘Is the second tone higher or lower than the first tone?’ in a two-alternative forced choice design [199]. Participants were instructed as follows: (1) to use the up arrow key on the laptop computer if they thought the second tone was higher or the down arrow key if they thought the second tone was lower, and (2) to respond within a 3s time window as their reaction times were also measured.

In order to determine the participants’ ability to discriminate relative pitch, both pre-training and post-training tests were administered without feedback on whether the participants’ responses were correct, incorrect or missing. In each test, a total of 420 pairs of tones were randomly presented to the participant during a period of approximately 50 minutes. Regular short pauses were allowed approximately every five minutes with one longer break of up to ten minutes available after twenty minutes of testing. The pairs presented were both ascending and descending in pitch and covered 12 music intervals ranging from a semi-tone to an octave over the frequency range C3 (130.8Hz) to B4 (493.9Hz). The entire set of interval pairs is provided in Table C.2, Section C.3 of Appendix C.

After completing the pre-training test, participants undertook sixteen short training sessions (one session per day) up to fifteen minutes each over a period of five to six weeks with a maximum inter-session gap of one week. In each training session, 72 interval pairs were presented from the complete set of 420 interval pairs. This involved six permutations chosen randomly from each of the twelve possible intervals. However, once an interval pair was presented it was not used again in the same session or any following session until all possible pairs for that particular interval had been exhausted. To facilitate learning, feedback was given to the participant on whether each response was correct, incorrect or missing during each training session. At the end of each session, the percentage of these responses was also given to the participant.

Before starting the test session, participants practiced with a short demonstration session that involved the presentation of six interval pairs for less than a minute. This enabled participants to familiarise themselves with the experiment while minimising any possible practice effect. The demonstration session also ensured that participants understood the instructions correctly.

The temperature of the fingertip, the ball of the forefoot and the heel was measured before and after each training session and each test using an infra-red thermometer. Based on the findings of Verrillo and Bolanowski [83] on the effect of temperature on vibrotactile thresholds, the acceptable temperature range for valid measurements was chosen to be 24 to 36ºC.

For the measurements on the forefoot, participants were asked to remove their footwear and roll their trousers or dress up to the right knee in order to avoid any sensation from their clothes.

The procedure was programmed in Matlab as a set of two graphical user interfaces (GUIs) that were run on the laptop computer (see Sections 3.2.2 and 3.3.2). This allowed automatic presentation of stimuli and facilitated the process of data collection. Additional details and figures for the GUIs are provided in the scripts for participants included in Section C.2 of Appendix C along with an example for the raw data collected in a pre-training test (see Section C.3).

5.4 RESULTS, ANALYSIS AND DISCUSSION

This section discusses the results from fingertips and forefeet of participants with normal hearing during the training period and the pre-training and post-training tests. A comparison of pre-training tests for participants with hearing impairments is also discussed.

Analysis was performed using SPSS software with either parametric (dependent *t*-tests) or non-parametric (Wilcoxon signed-rank or Mann-Whitney) tests. The assumptions for parametric data included (a) data measured at ratio level (i.e. scores), (b) normality of distribution, and (c) homogeneity of variance if different groups of participants were to be compared. Normality was checked using the Shapiro-Wilk test because of its sensitivity, even with small-sized samples [162].

5.4.1 Fingertips

Analysis was performed on the data collected in Liverpool and Manchester for participants with normal hearing and with hearing impairments. The results were reviewed and analysed independently for subsequent joint criticism and final agreement with co-researchers in Manchester.

5.4.1.1 Training

The results from the training period show the extent to which relative pitch can be correctly discriminated (Figure 5.3). The accuracy in relative pitch discrimination was > 70% from intervals of at least 3 semitones and > 90% from intervals of at least 8 semitones. Only a small number of responses in the range 0.1 to 0.6% were missing.

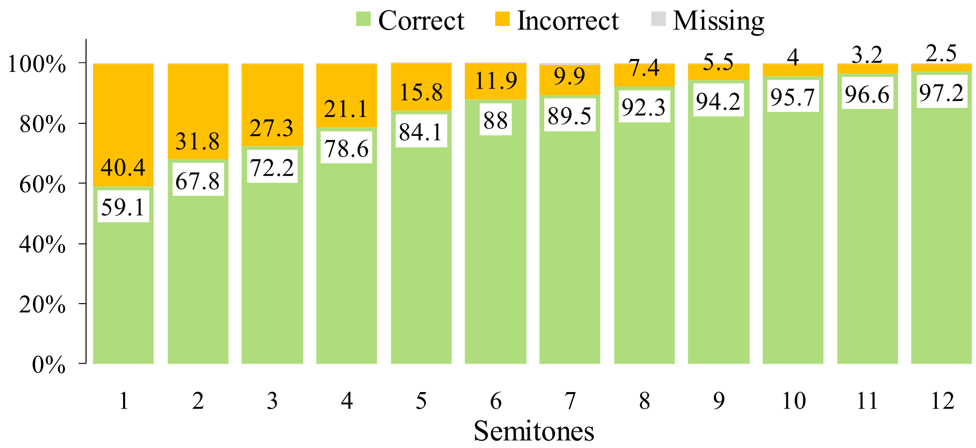

Figure 5.3 Mean percentage of responses using the fingertip shown at each interval size in semitones from all 17 participants and for all 16 training sessions.

Figure 5.4 indicates that the correct discrimination of relative pitch did not increase uniformly from one training session to the next. The straight-line trend of improvement $y = 0.28x + 82.13$ through the sessions was described by $R^2 = 0.452$, which indicates that the efficiency of the training between sessions may improve with improved feedback provided to the participants as discussed later in this chapter.

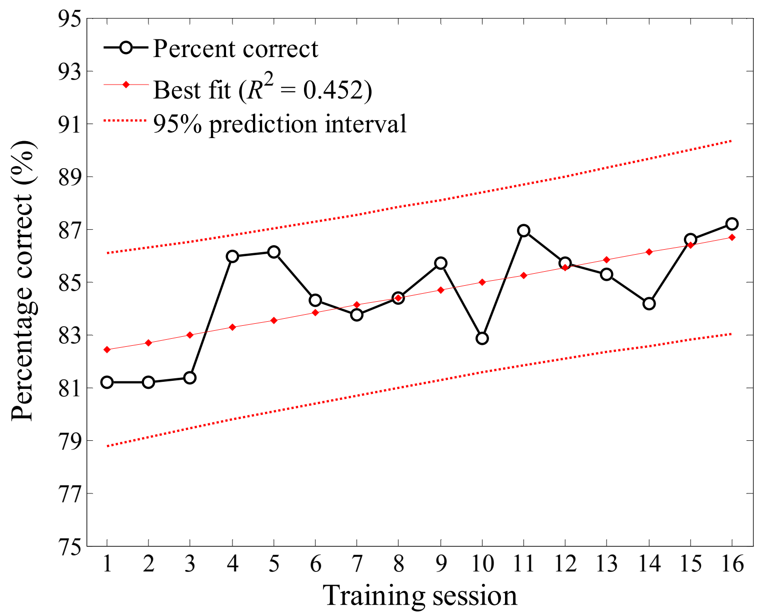

Figure 5.4 Mean percentage of correct responses using the middle fingertip in training sessions for all 17 participants. Prediction bounds indicate 95% confidence limits based on the straight-line fit [200].

5.4.1.2 Pre- and post-training

In order to assess further the benefits of training, Figure 5.5 shows a comparison of pre- and post-training results for each participant. Noticeable individual improvements were 7% and 8% for participants G and A, respectively and 13.6%, 16%, 17% and 20% for participants C, J, N and H, respectively. Otherwise, the improvement was only up to 3%.

Less than one-third of the participants showed small negative improvements: −1% for participants I, M, Q and −3% for participants E and P. Note that 1% corresponds to only four interval pairs out of the four hundred and twenty presented during each test. Only a small number of responses in the range 0.2 to 2% were missing in pre- and post-training tests across participants.

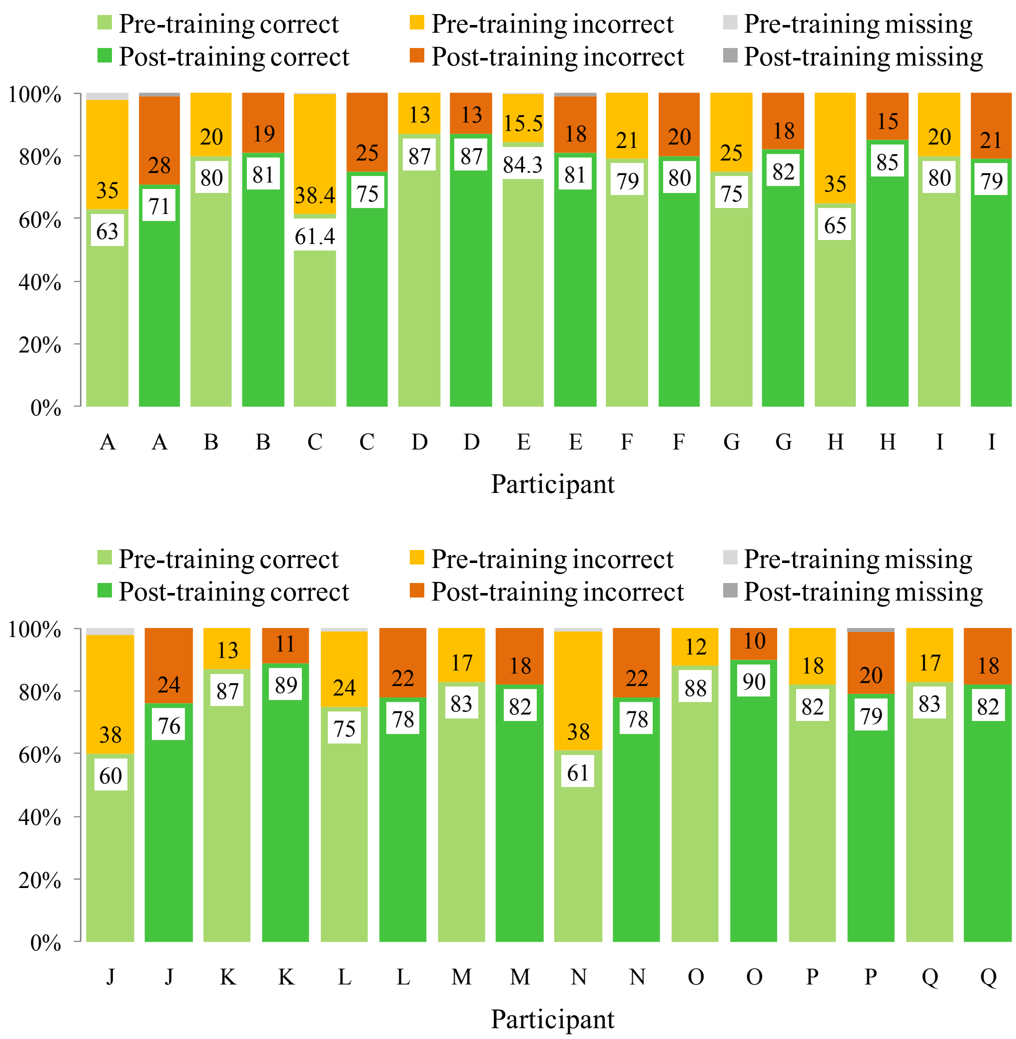

Figure 5.5 Percentage of the total number of responses using the middle fingertip, including all interval sizes, from 17 participants.

Figure 5.6 shows that the mean percentage of correct responses for each interval size between four and twelve semitones was > 70% for both pre-training and post-training tests. In post-training, effectively the same level of accuracy (> 69.5%) was achieved for smaller interval sizes, namely at the interval of three semitones. In addition, the mean percentage of correct responses for all intervals increased by 5%, from 78.3% in pre-training to 83.3% in the post-training test. These improvements may be considered to be the result of learning through the training period.

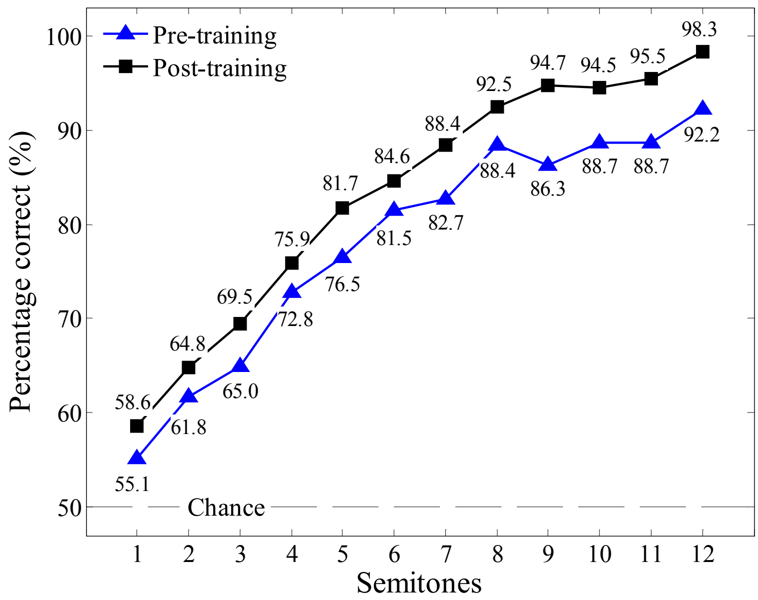

Figure 5.6 Comparison of mean percentage of correct responses using the middle fingertip from all 17 participants in pre- and post-training tests. Chance performance is represented by the horizontal dashed line.

Larger intervals were more accurately identified than smaller intervals. As expected, in both pre- and post-training tests there was a significant positive correlation ($p < 0.001$) between interval size in semitones and correct responses; thus, as the interval size increased, the number of correct responses increased. The Spearman correlation coefficient between these variables increased from $r = 0.66$ in the pre-training test to $r = 0.84$ in the post-training test. According to Cohen's benchmark [201], this represents a large-sized effect.

Grouping smaller intervals between one and six semitones showed a significant and appreciable improvement between pre- and post-training tests (dependent *t*-test, $p = 0.001$, $t(101) = 3.45$, $r = 0.32$). Grouping larger intervals between seven and twelve semitones showed a more substantive improvement (Wilcoxon, $p < 0.001$, $T = 542.5$, $r = -0.33$). For the individual intervals nine, ten, eleven and twelve semitones there was a significant improvement between pre- and post-training tests (Wilcoxon, $p < 0.05$) and the effect sizes were $r = 0.42$, 0.34, 0.35, and 0.34, respectively; the test statistic values were $T = 91$, 55, 85 and 32, respectively. These results indicate the extent to which larger intervals became easier to distinguish than smaller intervals as a result of training.

Using boxplots in Figure 5.7, the post-training results show a notably narrower spread than the pre-training results, except for the interval of two semitones (i.e. a whole tone). Note that the whisker for the interval of one semitone extends to include chance performance, although the median increased notably up to 8.7% from the pre- to the post-training test. The median values for intervals of two, three, five and seven semitones increased by ≈5%. However, the median for the interval of four semitones decreased by 5% and the interval of six semitones remained equal. These results generally indicate that the training period helped participants to distinguish intervals and reduced the variation in the responses between participants.

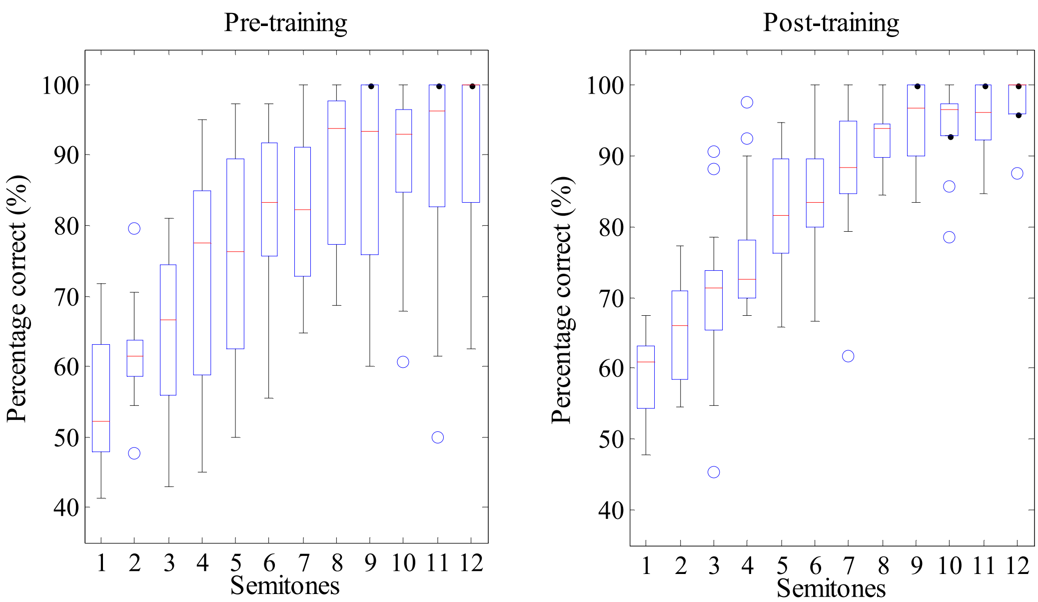

Figure 5.7 Mean percentage of correct responses using the middle fingertip from all 17 participants. Whisker marks indicate the extreme scores. The 25th and 75th percentiles form the edges of each box that contains the middle 50% of scores. The median is the red line. Circles represent outliers. Black dots indicate the absence of whiskers.

The results indicating the overall improvement at all intervals between pre- and post-training are shown on Figure 5.8. Both medians were different at the 5% significance level because their interval endpoints, indicated by the extreme points of the notches, do not overlap [165]. The mean percentage of correct responses in the post-training test was significantly higher (median = 87.5%) than in the pre-training test (median = 80.3%), $p < 0.001$, $T = 3888.5$, $r = -0.27$. This result supports the hypothesis that significant improvement in relative pitch discrimination can be obtained as a result of training.

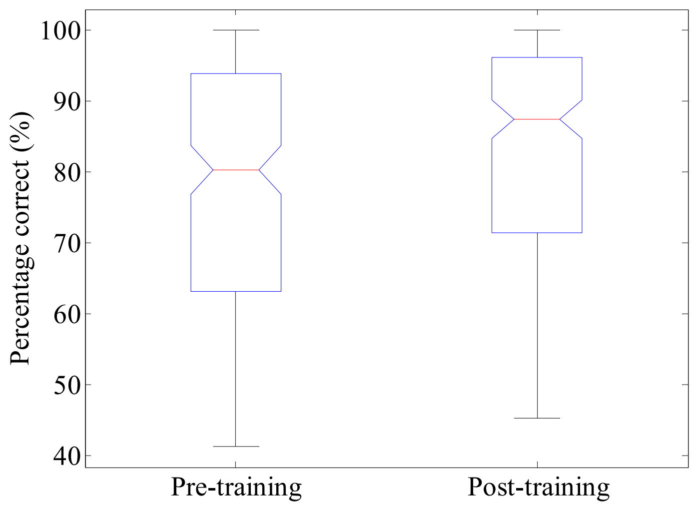

Figure 5.8 Box plots showing correct responses using the fingertip for all 12 intervals and all 17 participants.

Figure 5.9 shows the significant improvements between pre- and post-training tests for individual participants (dependent *t*-test, $p < 0.05$) representing a large-sized effect with *r*-values ≥ 0.67 for each case; the test statistic for participants A, C, H, J and N were $t(11) = 2.99$, 3.77, 5.75, 6.29 and 5.51, respectively.

Participants H, J and N had a particularly strong improvement (dependent *t*-test, $p < 0.001$) with *r*-values of 0.86. It is noteworthy that these five participants had the lowest scores (60 to 65%) in the pre-training test and training was seemingly more beneficial for them than for the participants achieving scores ≥ 75% in the pre-training test (see Figure 5.5). The non-significant results are shown in Figure C.1, Section C.3.1 of Appendix C.

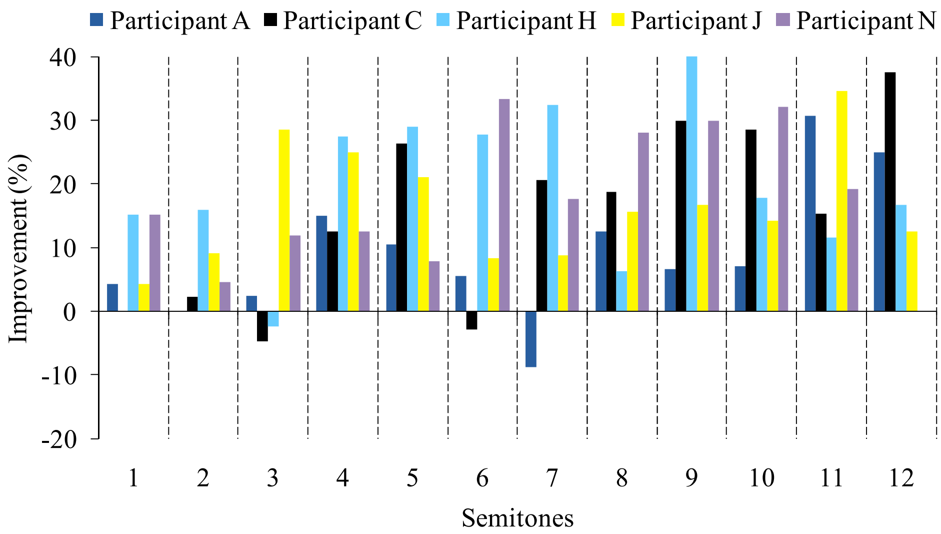

Figure 5.9 Significant improvement in the discrimination task using the fingertip comparing pre- and post-training tests for each participant and for each interval in semitones.

5.4.1.3 Reaction time

The reaction time during pre-training, training and post-training indicated the participants' ability to make a decision using the keyboard.

Figure 5.10 (left) shows that the mean reaction time for all participants was faster by 0.18s at the end of training. The decrease in reaction time showed a favourable trend using linear regression; the progression through training sessions explained 71.4% of the decrease in reaction time. The prediction bounds reflect a 95% certainty based on the straight-line fit. In addition, the correlation between both variables was significant ($p < 0.001$). This significance was due to the large dataset which included 19,584 small-varying time values ranging between 0.1s and 3s. However, the Spearman's correlation coefficient $r = -0.1$ corresponded to a small-sized effect. Thus, the faster reaction time by 0.18s (i.e. 1/16s) was not considered further.

Figure 5.10 (right) shows that participants B, F and P had a slower mean reaction time in the post-training test compared with the pre-training test, whilst the reaction from the remaining participants was faster or effectively the same. Moreover, the overall difference in these reaction times for all the 17 participants between pre- and post-training tests was not significant (Wilcoxon, $p > 0.05$, $T = 44$, $r = -0.26$).

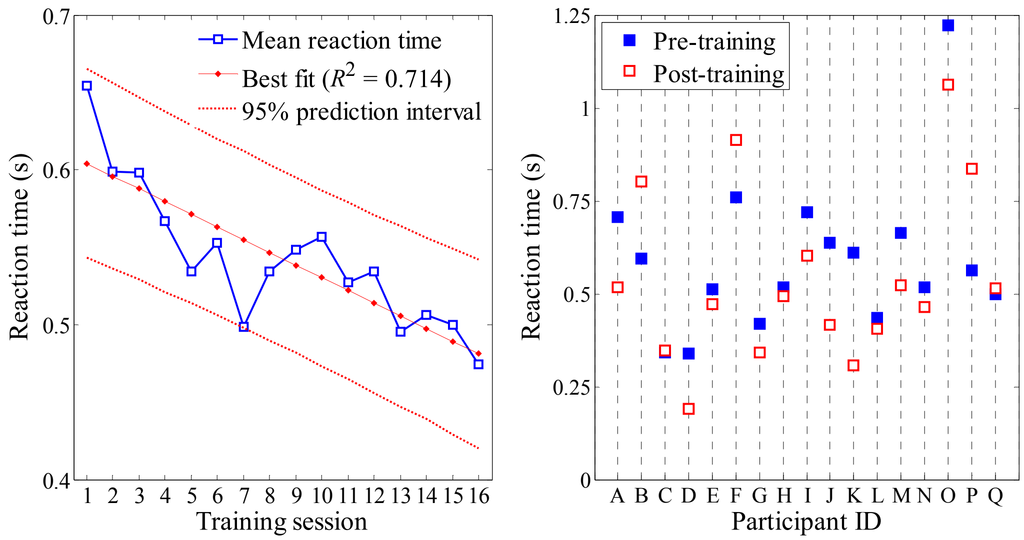

Figure 5.10 Mean reaction times using the middle fingertip from all the 17 participants in training sessions (left) and in pre-and post-training tests (right).

5.4.1.4 Pre-training test for participants with hearing impairments

The effect of severe and profound hearing impairments affecting relative pitch discrimination was investigated using the pre-training test only. Figure 5.11 shows that the group of seventeen participants with normal hearing had a higher mean value for the percentage correct than the group of five severely or profoundly deaf participants. The means for the percentage of correct responses for normal hearing and severely or profoundly deaf participants were 78.3% and 70.4%, respectively; the medians were 80.3% and 66%, respectively. The average difference of correct responses at each interval size in semitones between each group of participants was 7.9% for the means, and 5.4% for the medians.

However, Figure 5.11 shows that the 95% confidence intervals overlap due to the high variability in the group of severely or profoundly deaf participants, as explained below. The statistical results in Table 5.1 confirm that the difference between both groups of participants is not significantly different (Mann-Whitney, $p > 0.05$).

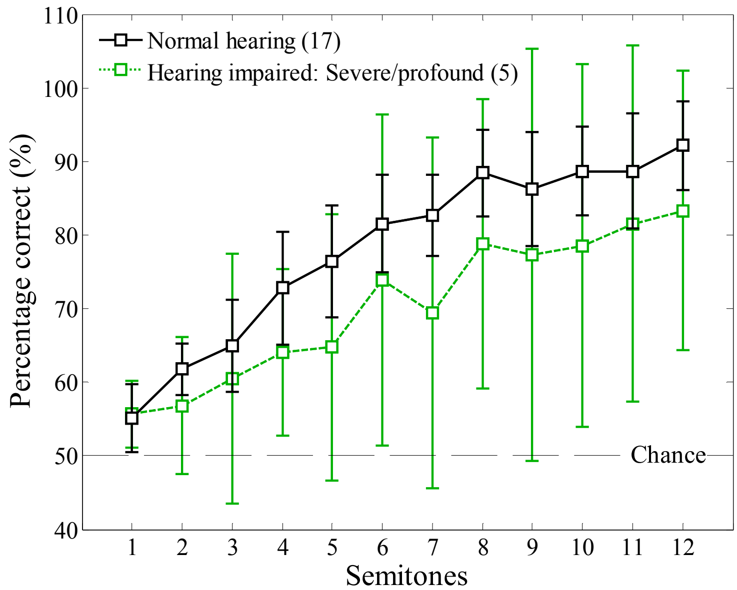

Figure 5.11 Mean percentage of correct responses using the middle fingertip in pre-training and 95% confidence intervals. Chance performance is indicated by the horizontal dashed line.

Table 5.1 Statistical results from the Mann-Whitney test to compare the test performance for the middle fingertip between participants with normal hearing and participants with severe/profound hearing impairments.

Semitones	*p*	*U*[a]	*r*
1	0.813	39.500	−0.051
2	0.383	31.500	−0.186
3	0.432	32.500	−0.168
4	0.182	25.500	−0.285
5	0.135	23.500	−0.319
6	0.325	30.000	−0.210
7	0.168	25.000	−0.294
8	0.123	23.000	−0.329
9	0.285	29.000	−0.228
10	0.216	27.000	−0.264
11	0.516	34.500	−0.139
12	0.066	20.000	−0.392

[a] Mann-Whitney test statistic.

Figure 5.12 illustrates that the total percentage of correct responses for three participants (V, W, X) out of the four participants with profound deafness was > 75%. These results were similar to the results from the participants with normal hearing (cf. Figure 5.5).

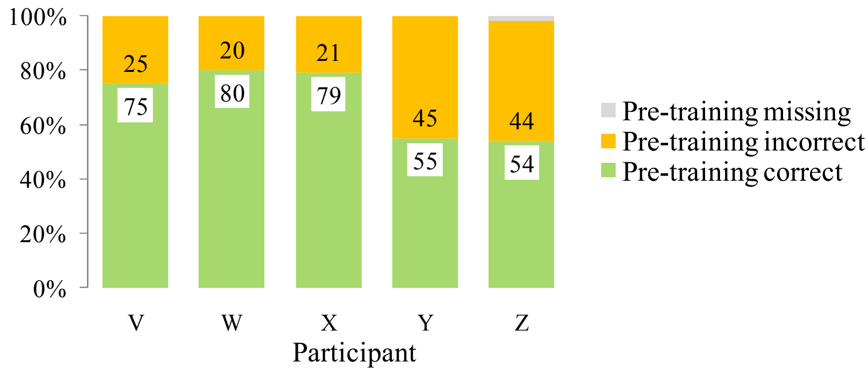

Figure 5.12 Total percentage of correct responses using the middle fingertip from participants V, W, X, Y with profound deafness and participant Z with severe deafness.

It is of note that the results from participants Y and Z with hearing impairments (who played a musical instrument or sang to an academic or professional extent) were close to chance (see Figure 5.12). This resulted in the wide 95% confidence intervals for the group of participants with hearing impairments shown in Figure 5.11. Results in Figure 5.12 are depicted in more detail in Figure 5.13 to show the mean percentage of correct responses for each interval size in semitones for the participants with hearing impairments. Figure 5.13 can then be compared with Figure 5.14 which shows the mean percentage of correct responses for each interval size in semitones for the participants with normal hearing who played a musical instrument or sang to an academic or professional extent.

The comparison between these two groups of participants who played a musical instrument or sang to an academic or professional extent included the above four participants with hearing impairments (cf. Figures 5.12 and 5.13) and the eight participants with normal hearing (cf. Figures 5.5 and 5.14). Table 5.2 shows no significant difference between both samples of participants (Mann-Whitney, $p > 0.05$), except for the interval of 12 semitones which showed a large effect size, $r = 0.62$.

These results would appear to add favourably to the hypothesis that there is no significant difference between detection thresholds of participants with normal hearing and with severe or profound hearing impairments, as discussed in Chapter 4. In order to expand on these results, additional participants with severe or profound deafness would be needed.

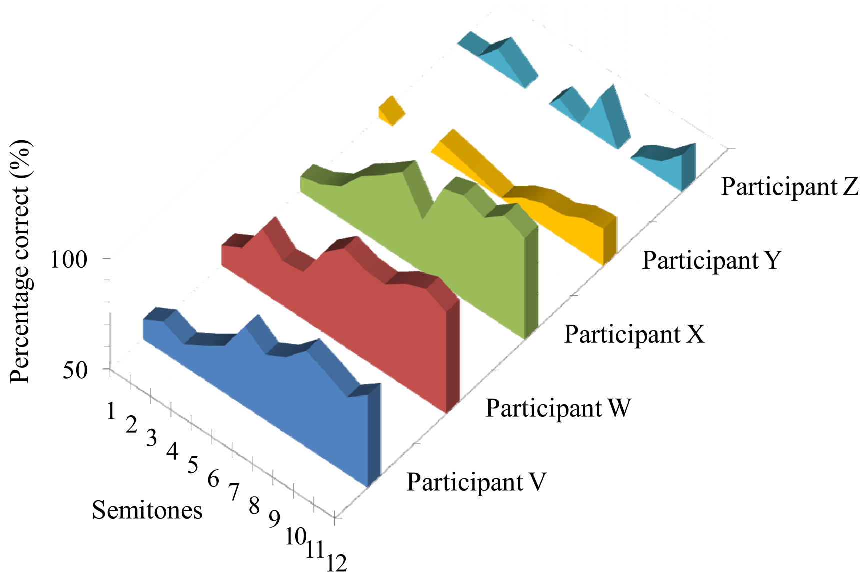

Figure 5.13 Mean percentage of correct responses using the middle fingertip in pre-training from participants V, W, X, Y with profound deafness and participant Z with severe deafness. These participants played a musical instrument or sang to an academic or professional extent, except participant V who had no musical skills.

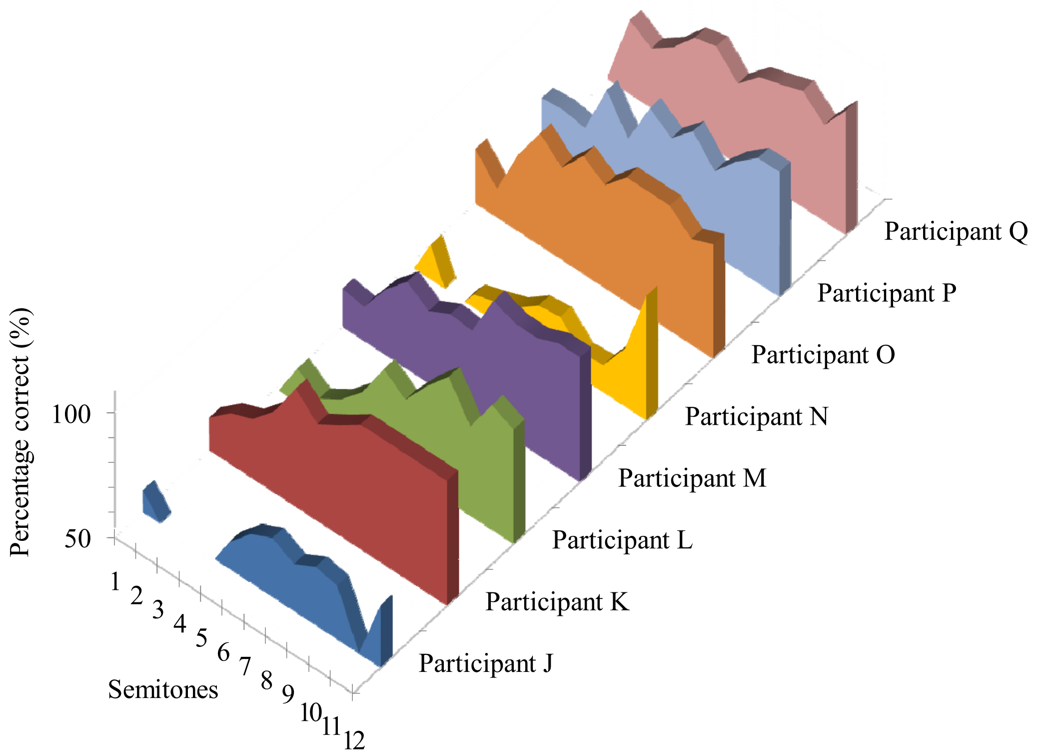

Figure 5.14 Mean percentage of correct responses using the middle fingertip in pre-training from a sample of eight out of seventeen participants with normal hearing (cf. Figure 5.5). These eight participants played a musical instrument or sang to an academic or professional extent.

Table 5.2 Statistical results from the Mann-Whitney test with participants who were musicians to compare the test performance of participants with normal hearing and those with hearing impairments.

Semitones	p	U	r
1	0.444	11.5	−0.221
2	0.083	6	−0.500
3	0.609	13	−0.148
4	0.234	9	−0.343
5	0.148	7.5	−0.417
6	0.172	8	−0.394
7	0.231	9	−0.346
8	0.192	8.5	−0.376
9	0.17	8	−0.396
10	0.229	9	−0.348
11	0.717	14	−0.105
12	**0.031**	4	**−0.623**

5.4.2 Forefeet

This section considers the results from the forefeet of participants with normal hearing and their relation to the above results with fingertips of participants with normal hearing. The measurements on the forefeet were performed in Liverpool.

5.4.2.1 Training

Figure 5.15 indicates a similar trend of increasing correct responses with increasing interval size as was observed with fingertips (cf. Figure 5.3). Only a small number of responses ranging from 0.2 to 0.8% were missing. Figure 5.15 shows correct scores > 70% when the interval size was at least four semitones. For intervals up to two semitones, the scores are similar to those of fingertips. However, correct discrimination on forefeet was lower for all intervals; for intervals between five and ten semitones, correct results for the forefeet were on average 7.8% lower than with fingertips.

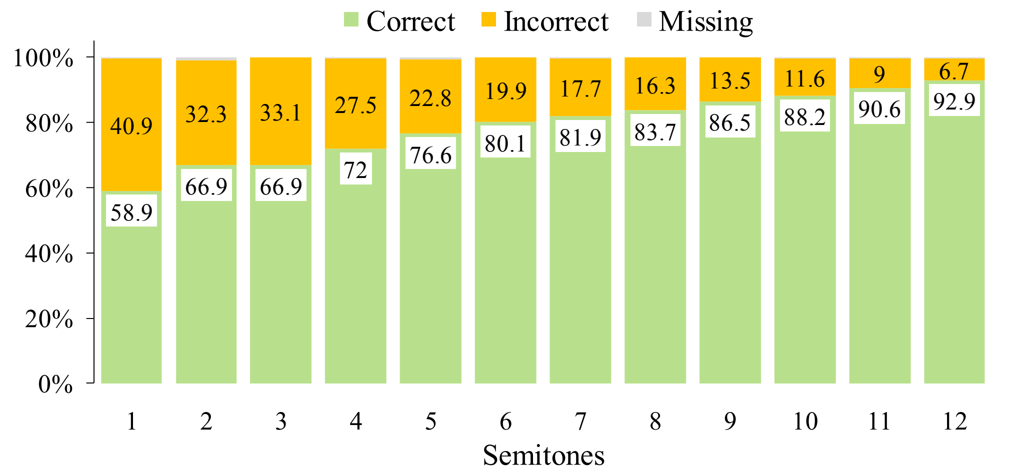

Figure 5.15 Mean percentage of responses shown at each interval size in semitones from all nine participants and for all sixteen training sessions.

Figure 5.16 indicates the mean percentage of correct answers for all participants over the training sessions. After the third session, the mean percentage of correct responses stabilised at 79% ±2%, which was approximately 6% lower than the mean percentage of correct responses for fingertips (85% ±2%). As with the fingertips, the results from one session to the next might improve by using feedback that is suited to individual degrees of ability. A similar number and duration of training sessions may still be used in agreement with previous studies that successfully trained participants with normal hearing [62, 130, 131, 198] and with hearing impairments [39, 127].

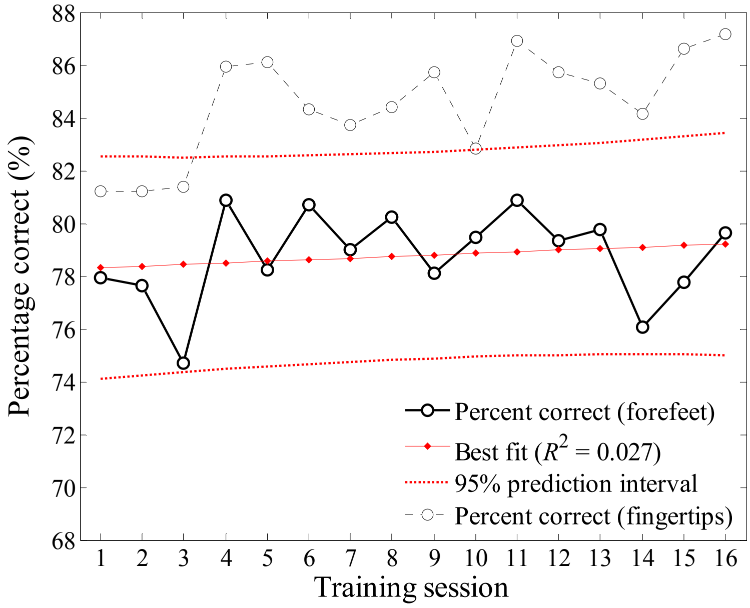

Figure 5.16 Mean percentage of correct responses in training sessions for all nine participants. Prediction bounds reflect a 95% certainty based on the straight-line fit [200].

5.4.2.2 Pre- and post-training

Pre- and post-training results were compared to assess further the benefits of training. Figure 5.17 illustrates the percentage increase of the total number of correct responses for all interval sizes which, on average, improved from 71.6% in the pre-training test to 78.5% in the post-training test. This improvement of 6.9% was only slightly larger than the improvement of 4.8% for fingertips (cf. Figure 5.5). This suggests that training with forefeet is similarly efficient to training with fingertips, even if the performance with forefeet generally had lower percentage of correct responses compared with that with fingertips.

Most participants achieved marked improvements, namely 5 to 7% for participants A, C', D, H and 10%, 10.6% and 16% for participants B, F, I, respectively. Participant C, who previously undertook the experiment on fingertips, was substituted by the new participant C'. There were no negative improvements and the range of missing responses in the pre- and post-training tests was 0.1 to 2%, except for one participant who had 4% missing responses.

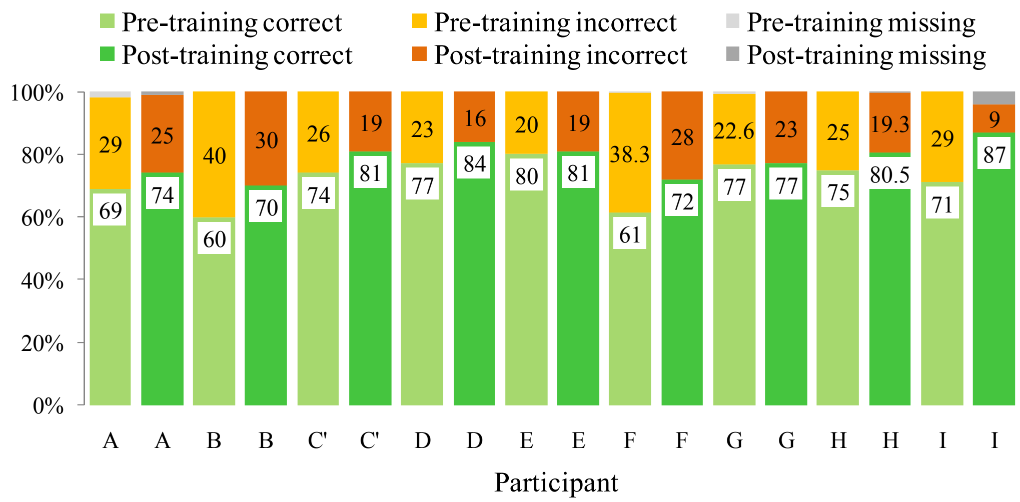

Figure 5.17 Percentage of the total number of responses, including all interval sizes, from all nine participants.

Figure 5.18 illustrates the performance with forefeet in relation to the performance with fingertips. The mean percentage of correct responses with forefeet for interval sizes starting at three semitones was $\geq 70\%$ in the post-training test. Correct scores $\geq 70\%$ were obtained in the pre-training test beginning at intervals of six semitones using forefeet, whereas the same score started at intervals of four semitones using fingertips. On average, the correct responses with forefeet increased from 73.6% in pre-training to 80.1% in post-training. This 6.5% increase was similar to the 5% increase with fingertips.

For the pre-training test, the difference between the results for fingertips and forefeet was only significant for the interval of six semitones (Mann-Whitney, $p < 0.05$, $U = 39$, $r = -0.40$). For the post-training test, it is noteworthy that the performance with forefeet had 5.9% more correct scores than fingertips at the smallest interval of one semitone. This higher accuracy with the forefeet diminished progressively up to the interval of three semitones and indicates that training provided a particular benefit for the discrimination of small-sized intervals (see Figure 5.18). The difference between the post-training results for fingertips and forefeet was significant for intervals of one and nine to eleven semitones (Mann-Whitney, $p < 0.05$) with U-values that ranged between 31 and 38.5, and a large-sized effect that ranged between $r = -0.40$ and $r = -0.49$; the difference was more significant for the interval of twelve semitones (Mann-Whitney, $p < 0.01$, $U = 30$, $r = -0.54$).

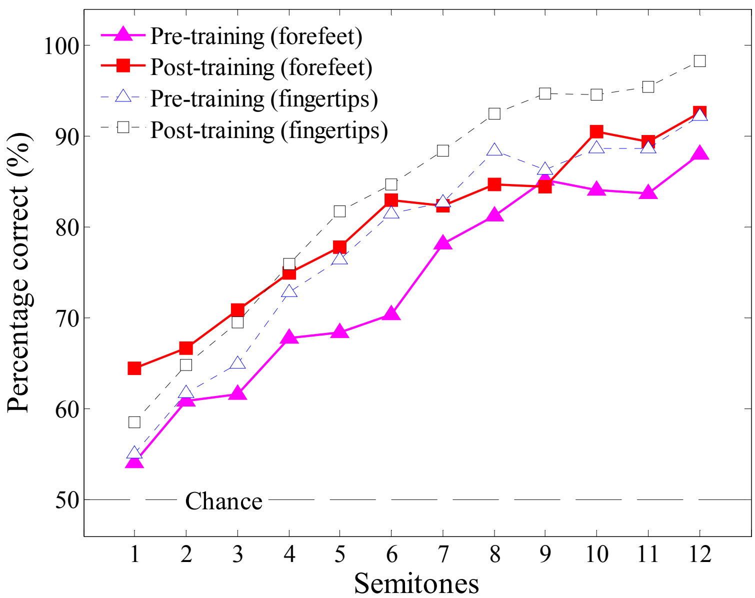

Figure 5.18 Mean percentage of correct responses using the forefeet and fingertips in pre- and post-training tests.

It is also noteworthy that there was no improvement at the interval of nine semitones in the post-training with forefeet, but the improvement was largest for this interval in the post-training of fingertips (see Figure 5.18). The reason for this feature was not identified and could possibly be physiological. This is because the frequency response and the uniformity of vibration of the contactor discs was satisfactory in the range of notes A3 (220Hz) to D4 (293.7Hz) that was included in the interval size of nine semitones (see Sections 3.2.1.1.D, 3.3.1.1.D, 3.3.1.1.E and Table C.2 in Section C.3 of Appendix C).

In both pre- and post-training tests with forefeet there was a highly significant positive correlation ($p < 0.001$) between the interval size in semitones and correct responses. The Spearman correlation coefficient between these variables was $r = 0.75$ in the pre-training test and $r = 0.72$ in the post-training test. This represented a large-sized experimental effect in both tests confirming that larger intervals are easier to distinguish than small intervals.

Further comparison between pre- and post-training tests in Figure 5.18 showed that the largest improvements using forefeet were for one semitone (dependent *t*-test, $p = 0.05$) and three, five and six semitones (dependent *t*-test, $p < 0.05$); the test statistic values were $t(8) = -2.30$, -2.86, -2.59 and -3.62, respectively. This represented a large-sized effect with *r*-values ≥ 0.63 for each of those intervals. This indicates that the training period was particularly effective for these intervals. This was in contrast to the fingertips where the largest improvements were for larger intervals, namely each interval between nine and twelve semitones.

For the forefeet, grouping intervals between one and six semitones indicated a highly significant improvement between pre- and post-training tests (dependent *t*-test, $p < 0.001$, $t(53) = -6.16$, $r = 0.65$) compared with grouping intervals between seven and twelve semitones (Wilcoxon, $p < 0.05$, $T = 787.5$, $r = 0.26$).

Figures 5.19 and 5.20 allow a comparison of pre- and post training results for all nine participants using boxplots, the medians of which are shown in Table C.3 for clarity (see Section C.3.2 of Appendix C). The post-training results with forefeet show a generally narrower spread compared with the pre-training results, which was also the case with fingertips. Although the accuracy of forefeet in the discrimination of one semitone was still close to chance performance, the median increased up to 13% in the post-training test (cf. Figure 5.18).

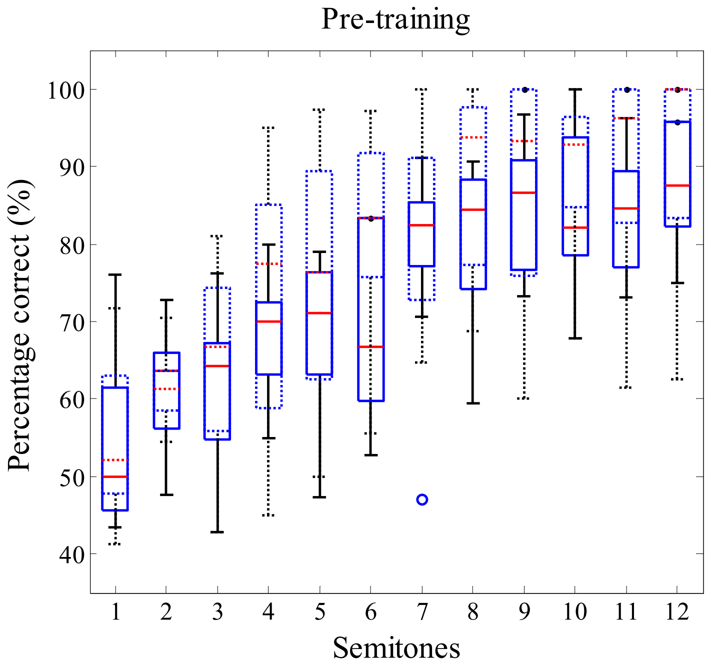

Figure 5.19 Mean percentage of correct responses using the forefeet (solid lines) and fingertips (dotted-lines) from the pre-training test.

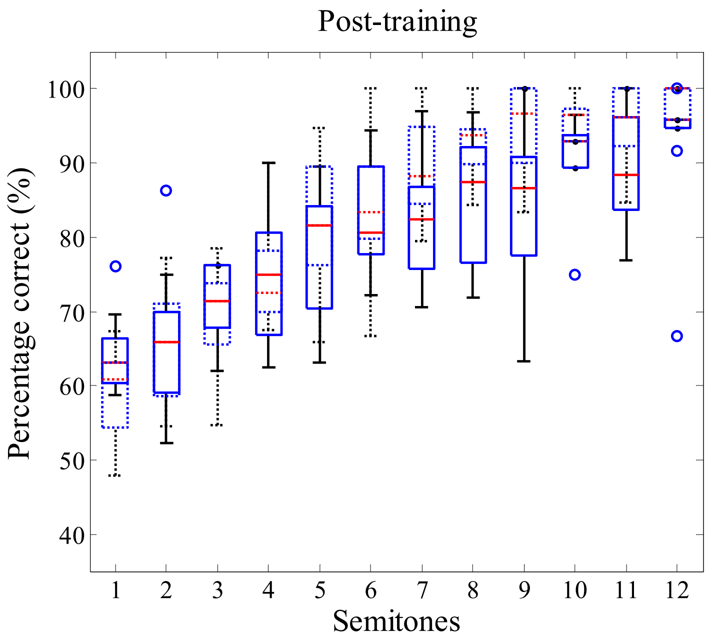

Figure 5.20 Mean percentage of correct responses using the forefeet (solid lines) and fingertips (dotted-lines) from the post-training test.

Figure 5.19 shows that the results from the pre-training test with forefeet had a narrower spread than with fingertips. However, this might be due to a practice effect because eight of the nine participants previously undertook the same discrimination task on fingertips.

The results for the overall improvement at all intervals and for all nine intervals between the pre- and post-training tests showed that the mean percentage of correct responses in the post-training test (median = 76.1%) was significantly higher than in the pre-training test (median = 80%), $T = 852$, $p < 0.001$, $r = -0.37$ (see Figure 5.21). This result supports the hypothesis that significant improvement in relative pitch discrimination on forefeet can be obtained as a result of training.

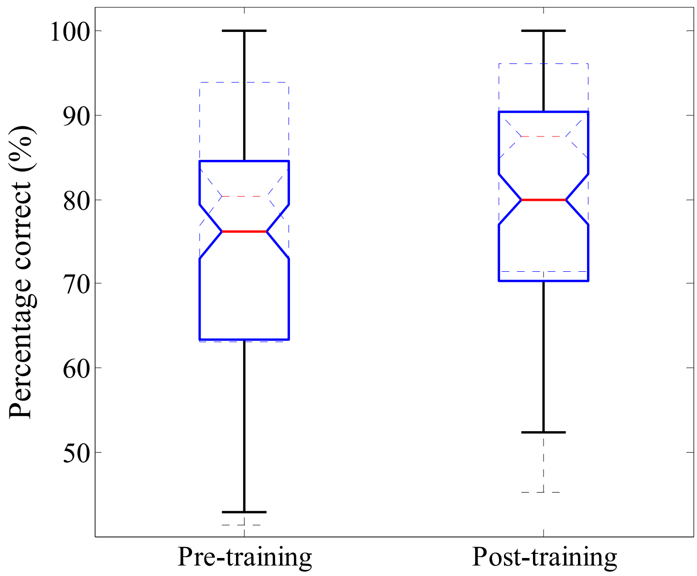

Figure 5.21 Box plots showing correct responses for all twelve intervals using forefeet (solid lines) and fingertips (dotted lines) for the pre-training and post-training tests.

In terms of individual participants, Figure 5.22 (top) shows the results of all the participants (C', D, F, I) who had a significant improvement between pre- and post-training tests (dependent *t*-test, $p < 0.05$). This represented a large-sized effect with *r*-values ≥ 0.59 for each participant. The test statistic values for participants C', D, F, I were $t(11) = -2.45$, -4.31, -4.71 and -4.51, respectively. Participants D, F, I had a particularly strong improvement (dependent *t*-test, $p = 0.001$) with *r*-values ≥ 0.79.

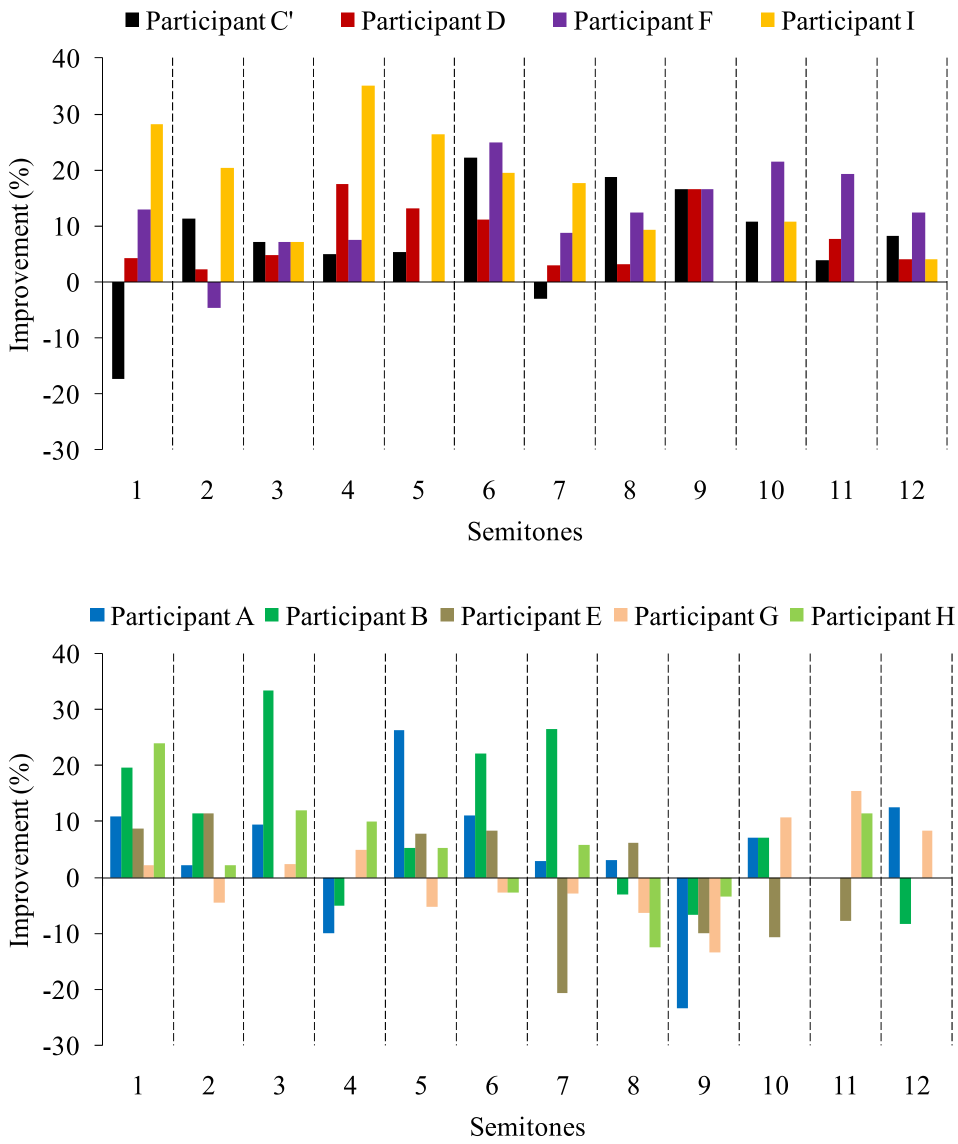

Figure 5.22 Significant improvement (top) and non-significant improvement (bottom) in relative pitch discrimination between pre- and post-training tests for each participant and for each interval in semitones. Significance defined by *t*-test ($p < 0.05$).

These improvements on forefeet were found to be relatively low for intervals of seven to twelve semitones compared with the improvements on fingertips which tended to increase with interval size in semitones (cf. Figure 5.9). In contrast, positive improvements on forefeet happened fairly frequently towards the low end of interval sizes such as one semitone, whilst improvement for fingertips tended to be less apparent in that low end of interval sizes (see Table C.3 in Section C.3.2 of Appendix C). This effect can also be seen in the improvements on forefeet and fingertips that were statistically non-significant (cf. Figure 5.22 (bottom) and Figure C.1 in Section C.3.1 of Appendix C). Figure 5.18 also shows significantly higher accuracy achieved with the forefeet in the post-training test for the interval of one semitone.

5.5 IMPLICATIONS FOR MUSICAL PERFORMANCE

The results in this chapter have provided the detailed extent to which discrimination of vibrotactile relative pitch is possible considering the experimental work from Chapter 4 regarding how to avoid adverse physiological effects from high vibration intensity. As suggested by von Békésy [161], Griffin [168], Geldard [114], Goff [117] and Morley and Rowe [197], the effects of high vibration intensity affecting the vibrotactile perception of pitch have also been considered in Section 5.3.1.

From a practical point of view, a suprathreshold level of approximately 10dB on the fingertip, forefoot or heel is the minimum that could be used. The suprathreshold level used in the present experiment was 15dB, which would allow for headroom within the three-octave range C3 (130.8Hz) to C5 (523.2Hz). Another advantage shown by Verrillo *et al* [116] is the shape of the vibrotactile contours of equal sensation levels which does not substantially change for suprathreshold levels of 15dB. In addition, there is a high degree of similarity between the contours of intensity for the hands and those for the ears.

Chapter 4 showed that the vibrotactile dynamic range is more limited than the auditory range [31]. The ability of the ears to discriminate frequency [202-204] is well known to be large when compared with the fingertip or the forefoot [120]. However, the present experiment has produced results similar to those for training using fundamental frequencies of musical tones in the auditory mode [198] and fundamental frequencies of speech in the tactile mode using pulse frequencies with participants with normal hearing and with hearing impairments [127], and also using single or multichannel systems for speech recognition [39, 53].

Sections 5.4.1.2 and 5.4.2.2 showed that it was possible to obtain > 70% of correct responses in the discrimination of intervals of four to twelve semitones using the middle fingertip with or without training and using the forefoot with training. This suggests that melody and chords could potentially be indentified effectively for music performance. A noteworthy fact was the lack of improvement at the interval of nine semitones in the post-training with forefeet, whilst the improvement was largest for this interval in the post-training with fingertips (see Figure 5.18). Yoo *et al* [135] has investigated similar effects in the perception of 80 vibrotactile two-note chords (also called intervals) assessed by 16 participants with normal hearing that could consistently describe vibrotactile consonance and dissonance resembling the perception of the corresponding auditory sensations.

Egloff *et al* [205] performed a psychophysical study that used simultaneous sinusoidal stimulation on the palm and the fingers of both hands of participants with normal hearing. These researchers found that the vibrotactile pitch could be accurately discriminated and the interval size of seven semitones (i.e. a perfect fifth [151]) could be identified on average with an accuracy > 90% in the range up to F4 (349.2Hz) with little or no training. This led to the conclusion that higher frequencies were not useful for music perception.

Weisenberger [53] concluded that fine-structure frequency cues could not be delivered by tactile transducers designed specifically to train speech for people with hearing impairments. However, the different nature of spectral content in speech and pure tones should perhaps be considered. Branje *et al* [206] used a different method to that in the present experiment and found a relative pitch discrimination as small as 400 cents (i.e. four semitones) using vibrotactile sinusoidal tones across the range C2 (65.4Hz) to C6 (1046.5Hz) presented to the back of participants. Hayes [129] has addressed limitations of vibrotactile feedback for music performance suggesting that spectral shifts may be less perceived than amplitude and frequency cues. Chauhan [134] has developed a violin for vibrotactile music performance incorporating octave shift and the quality experience was rated as considerably better than that with an amplitude modulation treatment.

The present experimental work has shown that at least 70% of the discrimination of relative pitch is correct for interval sizes of four to twelve semitones between C3 (130.8Hz) and C5 (523.2Hz) using the fingertip with or without training. In addition, training has been shown to be beneficial to improve significantly the discrimination for interval sizes between nine and twelve semitones using the fingertip and for intervals of one, three, five and six semitones using the forefoot.

Although the training period for fingertips and forefeet enabled participants to achieve high scores in the discrimination of relative pitch, the improvement from one training session to the next might have been expected to be increasingly larger. For the future it might be possible to gain higher scores by using selective feedback suited to individual degrees of ability (see Figures 5.9 and 5.22). In line with other studies [39, 127, 130, 131], the design and implementation of short-term training in the present study has been successful with daily practice over a relatively small number of weeks while avoiding long periods of inactivity during the training. However, Galvin *et al* [125] points out that the length of a successful training programme for participants with normal hearing and with hearing impairments increases with an increasing amount of different test stimuli and the difficulty in the training task. It may be noted that Rönnberg *et al* [126] trained 13 participants with a profound hearing impairment and showed that training efficacy is also directly dependent on the cognitive skills of the participants tested.

The results in Section 5.4.1.4 showed there was no significant difference in the accuracy of relative pitch discrimination between both groups of participants with normal hearing and with profound/severe hearing impairment. The exception to this was the significant difference found for the largest tested interval of 12 semitones when considering participants with musical skills only. Nevertheless, these outcomes would add favourably to the hypothesis confirmed in Chapter 4 that there is no significant difference between detection thresholds for both groups of participants.

Levänen and Hamdorf [207] used six participants with a profound hearing impairment and six participants with normal hearing. The task was to react only after having perceived the suprathreshold level change of a 180Hz stimulus within a sequence of 250Hz stimuli applied to the fingertip. The results showed a significant difference between both groups suggesting an enhanced sensitivity in participants with a profound hearing impairment. However, there was no significant difference between the results from both groups when using tone pairs in the range 160 to 250Hz in order to discriminate whether one tone was ascending or descending from the fixed reference tone of 200Hz in a pair.

In contrast, Frenzel *et al* [208] measured the vibration detection threshold using a sinusoidal stimulus at 125Hz delivered to the finger of 29 young participants aged 14 to 20 years with a severe congenital hearing impairment and an age-corrected control cohort of 286 participants. The results showed vibration detection thresholds that were significantly higher in the participants with the hearing impairment, which indicated a poorer sensitivity in this group. Perhaps, the participants' age may have played a role to obtain these results since young participants normally have significantly different sensitivity compared to older participants [91]. In addition, the sample sizes were remarkably different and perhaps a more balanced difference in the size of the sample may have produced different results.

Vibrotactile adaptation is an additional factor that may affect not only the detection of thresholds, as discussed in Chapter 4, but also relative pitch discrimination when performing music. According to Tommerdahl *et al* [85] and Goble and Hollins [209] vibrotactile adaptation enhances frequency discrimination at different frequencies closely below 50Hz and above 200Hz presented at suprathreshold levels, which would be important to include in guidelines for the design of vibrotactile devices such as those indicated by van Erp [210, 211] and Jones and Sarter [19].

Section 5.4.2.2 has shown that the forefoot is significantly more accurate that the fingertip to distinguish pitch in the post-training test at the smallest interval of one semitone in the range C3 (130.8Hz) to C5 (523.2Hz). In addition, Chapter 4 showed that the forefoot and the heel were more sensitive than the fingertip to detect thresholds at notes below approximately G2 (98Hz). Assuming that the practical dynamic range discussed in Chapter 4 would be similar for the forefeet and the accuracy of the forefoot to detect small intervals of one semitone in the post-training test can be extended to notes below C3, the presentation of small-sized intervals such as one or two semitones at relatively low levels between G1 (49Hz) and G2 (98Hz) to the forefoot rather than the fingertips would be more beneficial to enhance pitch perception. For this purpose, the presentation of single semitones or whole tones at higher levels between C3 (130.8Hz) and C5 (523.2Hz) to the forefoot would also help.

The experimental determination of musical pitch aspects so far may be considered a first step in the realization of a tactile device that can be used effectively in a practical music setting.

5.6 SUMMARY

Based on mean detection thresholds reported in the previous chapter, a two-octave range between C3 (130.81Hz) and C5 (523.25Hz) was used in this chapter because this corresponded to a relatively uniform range of maximum sensitivity at threshold. This allowed a comfortable presentation of stimuli at suprathreshold level within the available dynamic range in order to avoid adverse health effects that could be caused by long-term exposure to vibration.

The rigorous control of the intensity of test stimuli and the design of a comprehensive training program has allowed assessing the precise extent to which participants with normal hearing can discriminate musical intervals in the pre-training test. The correct discrimination of relative pitch using the middle fingertip was found to be relatively high compared with the forefoot. In terms of individual intervals, a mean percentage of correct responses ≥ 70% in the pre-training test occurred at intervals of at least four semitones using the fingertip in contrast to at least six semitones using the forefoot. However, except for the interval of six semitones, there was no significant difference (Mann-Whitney, $p > 0.05$) in the pre-training test between the results obtained with the fingertip and the forefoot.

An accurate assessment has also been made of the extent to which the relative pitch discrimination of participants with normal hearing can be learned and improved during the training. There was a clear trend of improvement in the accuracy of the discrimination task during training. For intervals up to two semitones, the mean percentage of correct responses obtained with the fingertip was comparable to that with the forefoot (i.e. 59% for one semitone and 68% for a whole tone). Using the forefoot, the success rate was ≥ 70% for intervals of four to twelve semitones with training, whilst the success rate with the fingertip was ≥ 70% for intervals of four to twelve semitones with or without training.

Comparing the results between pre- and post-training tests, the effect of training with the fingertip was found to be significant (Wilcoxon, $p < 0.05$) for intervals between nine and twelve semitones. In contrast, the effect of training with the forefoot was found to be significant for intervals of one (dependent *t*-test, $p = 0.05$), three, five and six semitones (dependent *t*-test, $p < 0.05$).

In the post-training test, the forefoot was significantly more accurate than the fingertip for the interval of one semitone (Mann-Whitney, $p < 0.05$), and significantly less accurate than the fingertip for intervals between nine and twelve semitones (Mann-Whitney, $p < 0.05$).

The above findings indicate that the training with the fingertip was more effective for large-sized intervals compared to the training with the forefoot; however, the forefoot was better trained than fingertips for smaller intervals. Consequently, most musicians may benefit in practice from the discrimination of vibrotactile relative pitch via their forefoot in order to use single notes as well as simple two-note chords and melodies while their hands are used to play a musical instrument.

As to the comparison of the performance in the pre-training test between both groups of participants with normal hearing and with severe or profound hearing impairments, there was no significant difference in the ability to discriminate relative pitch via fingertips (Mann-Whitney, $p > 0.05$). This was supported by the analysis of individual test performances from participants who had musical skills.

6 RELATIVE AND ABSOLUTE PITCH LEARNING

6.1 INTRODUCTION

This chapter describes the experiment designed to assess the learning of both relative pitch and absolute pitch identification using fingertips and forefeet. Absolute pitch refers to the ability to identify or recognise the pitch of an isolated musical tone without reference to a comparison tone [203, 212, 213]. Based on the research questions in Section 1.2.3 of Chapter 1, the main aims of the experiment were: (1) to define the extent to which pitch can be identified correctly using fingertips and forefeet and (2) to investigate how this ability can be improved with training.

The main sections of this chapter describe the participants, the objective and subjective measurement procedures for each test session, and the results with analysis and discussion.

6.2 PARTICIPANTS

This section provides details about participants in the experiment to test fingertips and forefeet. The entire set of participants had no self-reported impairment of sensation in their hands or feet and the samples of participants used in the analysis of experimental data were regarded independently of age, gender and cognitive skills.

6.2.1 Fingertips

Eighteen participants were recruited with normal hearing (nine female and nine male) that played a musical instrument and/or sang in a choir or vocal group to an academic or professional extent. Nine of these participants had auditory absolute pitch, which was tested online[3] prior to the subjective measurements described in Section 6.3.2. Two of the participants who did not have absolute pitch had knowledge of the experimental design that other participants did not have. The age of the participants was in the range 19 to 57 years (mean: M = 23.9, standard deviation: σ = 8.8). Only 1 participant was aged 57 years, 1 participant was aged

[3] http://perfectpitch.freehostia.com (accessed: 7 February 2013)

30 years, and the remaining 16 participants were aged between 19 and 27 years. Participants were right-handed and carried out the experiment using the fingertip of the middle finger on the right hand. Approval for the experiment was given by the Research Ethics Committee of the RNCM. Participants were recruited and tested by co-researchers in Manchester.

6.2.2 Forefeet

Fifteen participants were recruited (seven female and eight male). Nine of these participants played a musical instrument and/or sang in a choir or vocal group to an amateur ability. The remaining six participants had no musical skills. None of the participants had absolute pitch, which was tested via the aforementioned online test. One of the participants had knowledge of the experimental design that other participants did not have due to involvement in the AHRC project. The age of the participants was 21 to 41 years ($M = 26.9$, $\sigma = 5.0$). Only 1 participant was aged 41 years, 3 participants were aged between 30 and 32 years, and the remaining 11 participants were aged between 21 and 27 years. Participants were right-handed and carried out the experiment using the right foot. Approval for the experiment was given by the Research Ethics Committee of the University of Liverpool. Participants were recruited and tested by the author in Liverpool.

6.3 PROCEDURE

The procedures to perform objective and subjective measurements on relative and absolute pitch identification were similar for both the fingertip and the forefoot (see Sections 3.2.3 and 3.3.3, respectively). However, the apparatus, the graphical user interfaces and the scripts for participants were adapted from the set-up used for the fingertip to the set-up for the forefoot.

The portable equipment developed at Liverpool and described in Section 3.2.3 was taken to Manchester to test the fingertips of participants. Afterwards, the equipment was returned to Liverpool to test the forefeet of participants using the set-up described in Section 3.3.3.

The required documents for research ethics such as the recruitment advertisement and the information sheet were similar to those from the previous experiment in relative pitch discrimination. The consent form and the questionnaire remained the same as in Appendix B, except for the title and the date information on the consent form (see Sections B.1.3 and B.1.4, respectively).

6.3.1 Objective measurements

The musical notes were effectively the same as in the experiment on relative pitch discrimination in Section 5.3.1. However, note C5 was added to complete the required range of test tones used in the procedure for subjective measurements (see Table C.1 in Section C.1 of Appendix C). Because this note radiated the highest level in the range of test tones, the masking noise level averaged for both ears was increased to 78dB L_{Aeq} to ensure it was effective.

6.3.2 Subjective measurements

The subjective measurements in this experiment were primarily concerned with the identification of relative pitch and absolute pitch, which was a considerably more demanding task for participants than the discrimination of relative pitch described in Chapter 5. Weisenberger [53] noted the hierarchy of tasks involved in the analysis of acoustic stimuli and stated that “identification is typically described as the task of isolating the unique features of a stimulus leading to the ability to name that stimulus”.

The procedure to perform subjective measurements was mostly designed by co-researchers in Manchester and consisted of nine sessions in total. Each session took place on a different day over a maximum period of four weeks with a maximum inter-session pause of one week. Each session included a study period followed by tests 1 and 2 as described below.

Study: During the study period, participants used the piano keyboard to familiarise themselves with the vibration produced by each of the notes that were active and therefore highlighted on the laptop screen. This period was divided into two parts: The first part of each session lasted 30s to study the tone C4. The second part lasted 1.5m to study all the active tones on the piano keyboard, i.e. C3 (130.8Hz), C4 (261.6Hz) and C5 (523.3Hz) for the first session. For the second and subsequent sessions, the length of the second part of the study period was longer due to a larger number of active tones to study.

After the study period, tests 1 and 2 consisted of a series of tone pairs that were randomly presented to participants. Each tone in a pair lasted one second with a one-second pause between them.

Test 1: The first tone in a pair was always C4, followed by any of the highlighted tones on the laptop screen in order to test relative pitch identification.

Test 2: The same tone was played twice in a pair and this tone could be any of the highlighted tones on the laptop screen in order to test absolute pitch identification.

In both tests, after each pair of tones was presented, participants were asked the question "Which note was it? Choose your answer on the piano". Participants had a maximum of three seconds to respond and were provided with feedback as to whether the response was correct, incorrect or missing before proceeding to the next pair of tones.

Overall, eleven tones were used in the experiment corresponding to the white notes C, D, E, G and A in a pentatonic scale between C3 and C5. The reason for this choice was due to the results on the experiment on relative pitch discrimination described in Chapter 5, which showed that the interval of one semitone was not consistently identified. The pentatonic scale was therefore a choice that includes a minimum interval of two semitones and is commonly used throughout the world [214, 215] and in recent training methods using vibrotactile gloves [130, 131].

For the first session, each test included three different pairs using C3, C4 and C5 and each pair was presented three times randomly. Therefore, a total of nine tone pairs were presented in the first session. The number of test tones and pairs increased progressively per session and each tone pair was always repeated three times in each session. Thus, the ninth and last session included eleven pairs of tones giving a total of thirty-three tone pairs in that session. The highlighted notes used in the experiment are provided in Figure 6.1

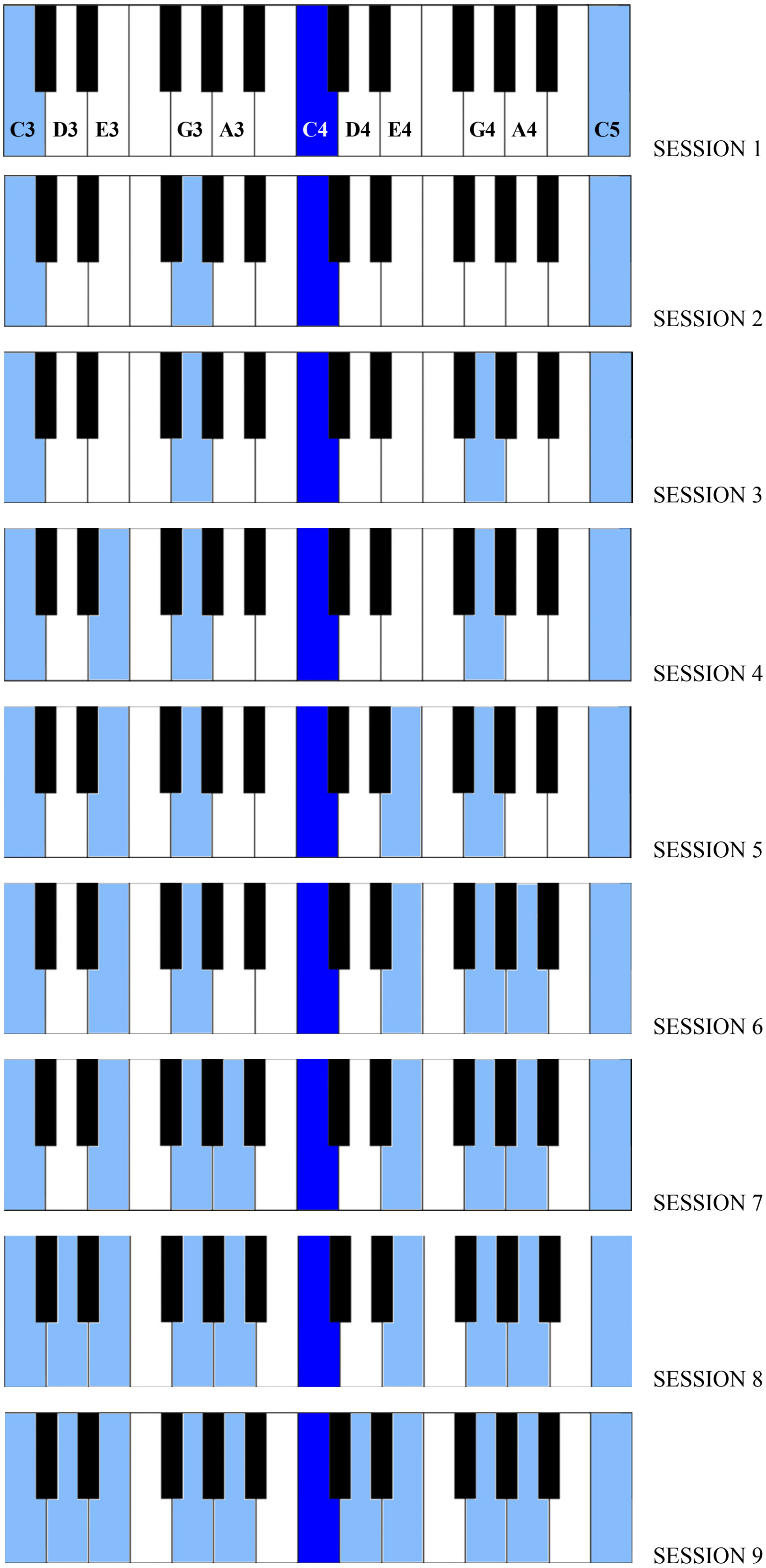

Figure 6.1 Notes used in each experimental session are highlighted in blue.

The total duration of the sessions, including the study period, ranged from approximately four minutes in the first session increasing up to approximately fifteen minutes in the ninth session. Participants were only briefed before starting the first session and this briefing took approximately 15 minutes including a short demonstration session that involved a one-minute study period and five pairs of tones randomly presented in each of both tests. The demonstration session enabled participants to familiarise themselves with the experiment and ensured that participants understood the instructions correctly. The full script used to brief the participants is in Section D.1 of Appendix D.

The temperature was measured at the fingertip and the ball of the forefoot before and after each test using an infra-red thermometer. As in the previous experiments, the acceptable temperature range for valid measurements was chosen to be 24 to 36ºC and participants were asked to remove their footwear and roll their trousers or dress up to the right knee.

The procedure was implemented as a graphical user interface (GUI) for automatic presentation of stimuli and data collection. Additional details and figures for the GUI are provided in the scripts for participants (see Section D.1 of Appendix D). An example of the data output at the end of an experimental session is provided in Section D.2.

6.4 RESULTS, ANALYSIS AND DISCUSSION

This section discusses the results from measurements performed on fingertips and forefeet of participants with normal hearing during the study period and tests 1 and 2.

Although the data for fingertips and forefeet were collected in Manchester and Liverpool, respectively, the results were prepared and analysed independently for subsequent joint criticism and final agreement with co-researchers in Manchester. The analysis with SPSS software used either parametric (independent *t*-tests) or non-parametric (Wilcoxon signed-rank) tests.

6.4.1 Fingertips

6.4.1.1 Pitch identification in tests 1 and 2

Figure 6.2 shows that tones C3, C4 and C5 in the first session were typically the easiest to identify with almost total accuracy. However, adding a new tone in each session made the identification task more difficult and caused performance to decrease progressively due to the increasingly large variety of choices presented to the participant. The correct pitch identification in tests 1 and 2 was very similar, without any significant difference between the tests (Wilcoxon, $p > 0.05$, $T = 4898.5$, $r = -0.02$).

These results indicate that training did not improve the identification of relative and absolute pitch over the sessions. Although the interval distances used were the same as in the previous experiment on relative pitch discrimination, except for one, six and eleven semitones, the correct pitch identification in the present experiment was lower than expected. This would appear to indicate the different nature of the discrimination and identification tasks.

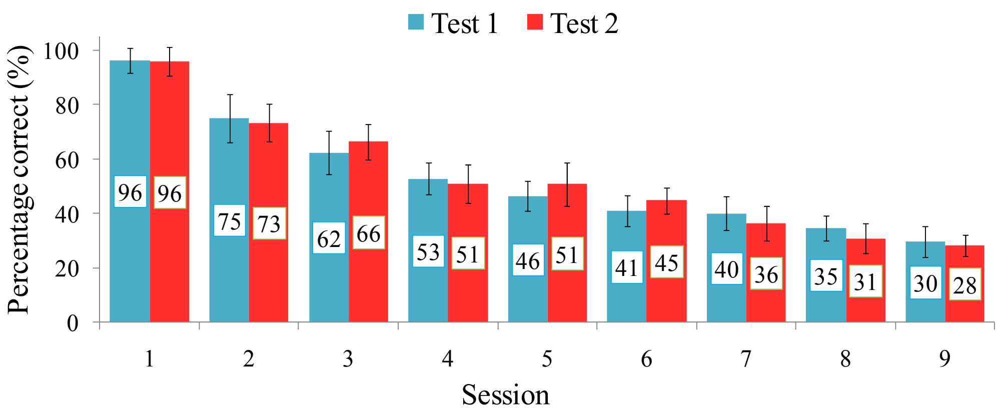

Figure 6.2 Total percentage of correct responses for tests 1 and 2 in each session using the middle fingertip. The error bar indicates the 95% confidence interval.

6.4.1.2 Study period and test performance

Figure 6.3 shows the data from Table 6.1, i.e. the total percentage of times that keys were pressed during the study period and the mean percentage of correct responses in tests 1 and 2 for all sessions using the middle fingertip.

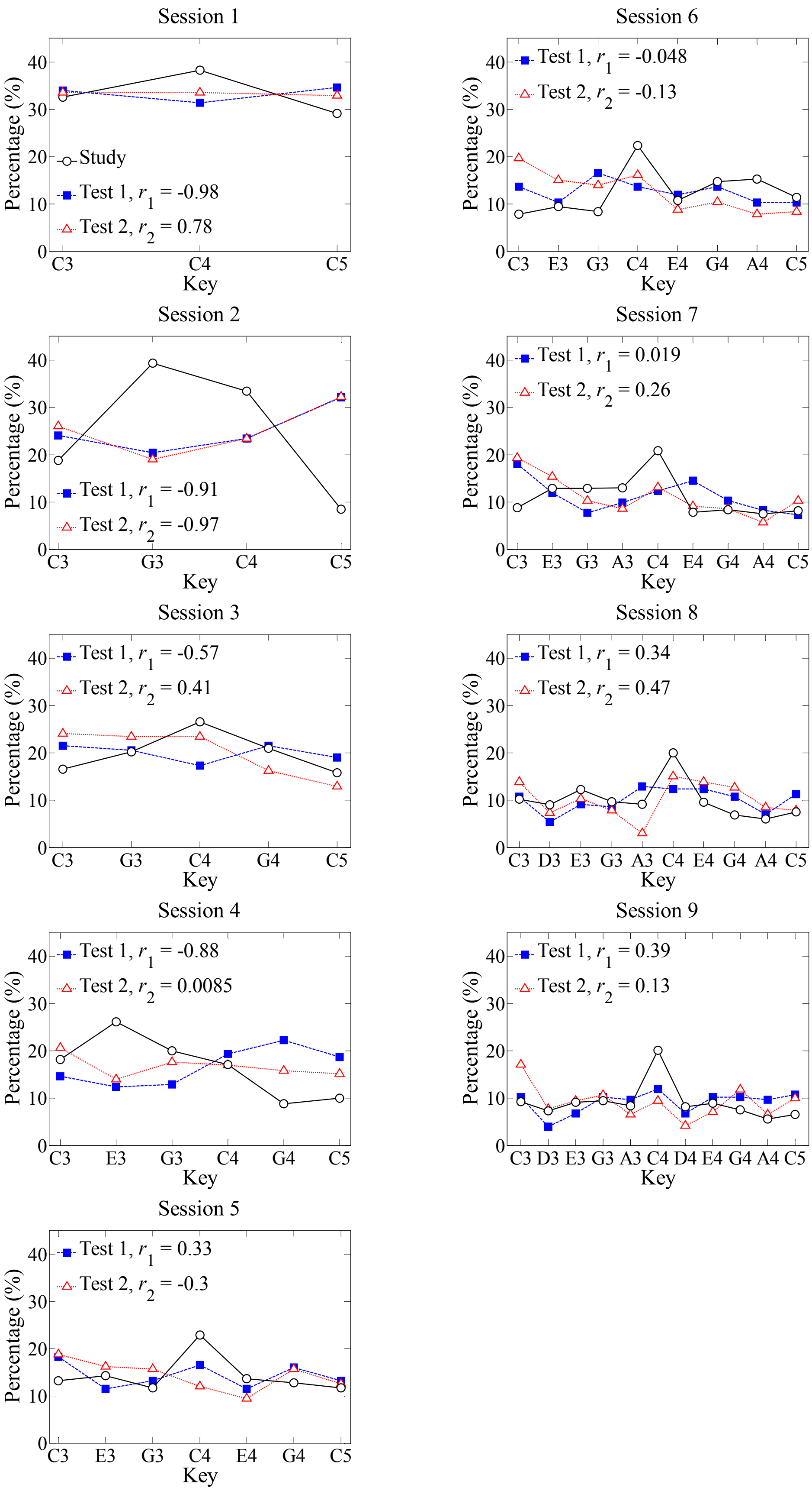

Figure 6.3 Total percentage of times pressing keys in the study (—○—) and mean percentage of correct responses in test 1 (—■—) and test 2 (···Δ···) with the fingertip (cf. Table 6.1). Correlation coefficients r_1 and r_2 relate to test 1 and test 2, respectively.

Table 6.1 Percentage of times each key was pressed in the study period and the difference between test 1 (T1) for the identification of relative pitch and test 2 (T2) for the identification of absolute pitch in terms of the percentage of correct scores using the middle fingertip. Negative values are marked in bold font and indicate that the score in test 1 was lower than the score in test 2.

Fingertip session		C3	D3	E3	G3	A3	C4	D4	E4	G4	A4	C5
1	Study	32.56					38.28					29.15
	T1	33.97					31.41					34.61
	T2	33.55					33.55					32.90
	T1−T2	0.42					**−2.14**					1.71
2	Study	18.78			39.35		33.47					8.40
	T1	24.07			20.37		23.46					32.10
	T2	25.95			18.99		23.42					32.28
	T1−T2	**−1.88**			1.38		0.04					**−0.18**
3	Study	16.56			20.19		26.50			20.97		15.78
	T1	21.43			20.48		17.26			21.43		19.05
	T2	24.02			23.46		23.46			16.20		12.85
	T1−T2	**−2.59**			**−2.98**		**−6.20**			5.23		6.20
4	Study	18.14		26.07	19.97		17.07			8.81		9.94
	T1	14.62		12.28	12.87		19.30			22.22		18.71
	T2	20.61		13.94	17.58		16.97			15.76		15.15
	T1−T2	**−5.99**		**−1.66**	**−4.71**		2.33			6.46		3.56
5	Study	13.14		14.27	11.69		22.84		13.60	12.81		11.65
	T1	18.28		11.43	13.14		16.57		11.43	16.00		13.14
	T2	18.75		16.15	15.63		11.98		9.38	15.63		12.50
	T1−T2	**−0.47**		**−4.72**	**−2.49**		4.59		2.05	0.37		0.64
6	Study	7.84		9.47	8.38		22.33		10.69	14.70	15.21	11.38
	T1	13.63		10.23	16.48		13.64		11.93	13.64	10.23	10.23
	T2	19.68		15.03	13.99		16.06		8.81	10.36	7.77	8.29
	T1−T2	**−6.05**		**−4.80**	2.49		**−2.42**		3.12	3.28	2.46	1.94
7	Study	8.81		12.86	12.89	12.96	20.80		7.77	8.31	7.50	8.10
	T1	18.04		11.86	7.73	9.80	12.37		14.43	10.31	8.25	7.22
	T2	19.32		15.34	10.23	8.52	13.07		9.10	8.52	5.68	10.23
	T1−T2	**−1.28**		**−3.48**	**−2.50**	1.28	**−0.70**		5.33	1.79	2.57	**−3.01**
8	Study	10.13	9.00	12.24	9.64	9.10	20.01		9.58	6.88	5.97	7.50
	T1	10.70	5.34	9.10	8.56	12.83	12.30		12.30	10.70	6.95	11.23
	T2	13.86	7.23	10.24	7.83	3.01	15.06		13.86	12.65	8.43	7.83
	T1−T2	**−3.16**	**−1.89**	**−1.14**	0.73	9.82	**−2.76**		**−1.56**	**−1.95**	**−1.48**	3.40
9	Study	9.22	7.28	9.08	9.46	8.36	20.05	8.14	8.92	7.50	5.51	6.48
	T1	10.17	3.95	6.78	10.17	9.60	11.86	6.78	10.17	10.17	9.60	10.73
	T2	17.06	7.65	9.41	10.59	6.47	9.41	4.12	7.06	11.76	6.47	10.00
	T1−T2	**−6.89**	**−3.70**	**−2.63**	**−0.42**	3.13	2.45	2.66	3.11	**−1.59**	3.13	0.73

Figure 6.3 includes the correlation coefficients r_1 and r_2 which indicate the relation between the study period and the performance in test 1 for relative pitch and test 2 for absolute pitch, respectively. The coefficients tend to be relatively

small or negative indicating that the proportion between the amount of study and the correct identification of notes was not constant and that the performance in the tests does not depend on the amount of study. However, the correct identification for the first three or four sessions was the highest due to the low number of tones, which made the identification task easier.

Between C3 and G3, the correct identification of absolute pitch was typically higher than the correct identification of relative pitch in most of the sessions (see Table 6.1). Except for the second and fourth sessions, the reference C4 was the most studied tone in each session by 10.1% on average. However, Figure 6.3 shows that this was not of any particular help in the identification task. Between A3 and C5, the correct identification of relative pitch was typically higher than the correct identification of absolute pitch in most of the sessions. An exception to this was for C4. It is possible that presenting C4 twice in the same pair of tones to identify relative pitch may have disconcerted some participants who might have expected the second tone in the pair to be different to the reference tone.

In general, the correct identification of relative pitch was typically higher for pitches between A3 and C5 compared with the correct identification of absolute pitch. However, the correct identification of absolute pitch was typically higher for lower pitches between C3 and G3 compared with the correct identification of relative pitch.

6.4.1.3 Response change per semitone away from a new note

The mean change in the percentage of correct responses in the identification task was assessed as a function of the interval distance in semitones between a newly introduced tone and the active tones in a test session. The response change was obtained by considering the total percentage of correct responses in each test and all sessions. For each key, the decrease in the total percentage of correct responses between adjacent sessions was divided by the number of semitones that a new tone in a session was separated from an active note. Finally, the total result for each interval size in semitones was averaged. The full details of this procedure are provided in Section D.2 of Appendix D.

This revealed the extent to which the correct responses were affected in relation to the proximity between a new tone and the active tones. Figure 6.4 shows that small interval distances between two and five semitones produced a notable decrease in the mean percentage of correct responses. This was due to a confusion effect or a perceptual similarity experienced by the participants when they had to identify tones that were relatively close to each other.

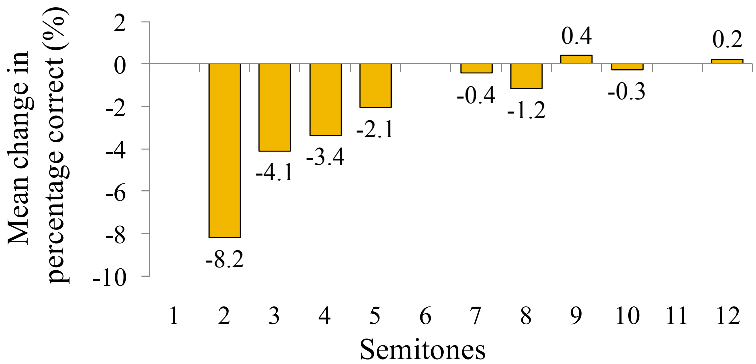

Figure 6.4 Mean change in the percentage of correct responses per semitone of distance away from a new tone using the middle fingertip. The interval distance on the *x*-axis indicates the number of semitones between the active test tones and a newly introduced test tone in a session. The pentatonic scale did not include interval distances of one, six and eleven semitones.

However, when the interval distance was seven semitones or more the change in the percentage correct was very small, typically ±1%; hence, any adverse effect was small as the interval distance increased. This explains the progressive decrease in correct responses as the number of training sessions increased, as shown in Figure 6.2.

6.4.2 Forefeet

This section considers the results from the forefeet of the participants and their relation to the above results measured on the fingertips.

6.4.2.1 Pitch identification in tests 1 and 2

Figure 6.5 shows that C3, C4 and C5 in the first session were the easiest to identify with a relatively high degree of accuracy using the forefoot. As with the fingertip, adding a new tone in each session caused the pitch identification to decrease progressively, without any significant difference between both tests

(Wilcoxon, $p > 0.05$, $T = 2790.5$, $r = -0.07$). As before, the training did not improve the identification of relative and absolute pitch over the sessions and the performance tended to be lower than with the previous section on relative and absolute pitch identification using fingertips.

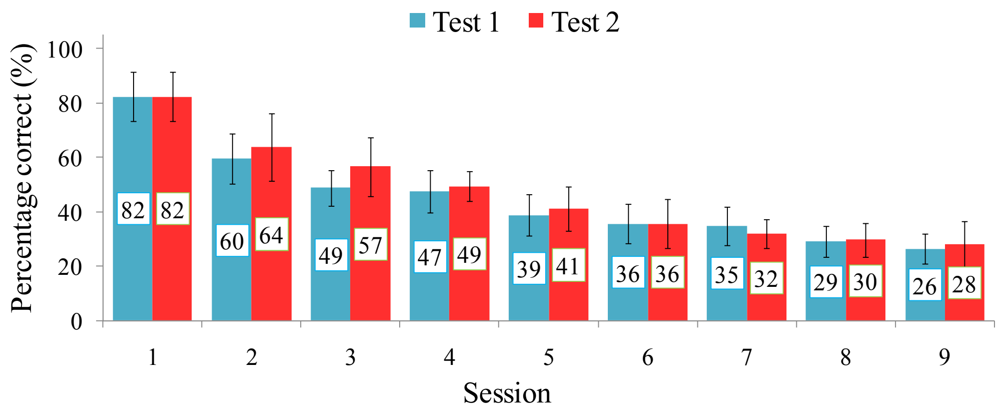

Figure 6.5 Total percentage of correct responses for tests 1 and 2 in each session using the forefoot. The error bar indicates the 95% confidence interval.

6.4.2.2 Study period and test performance

Figure 6.6 shows the data from Table 6.2, i.e. the total percentage of times that keys were pressed during the study period and the mean percentage of correct responses in tests 1 and 2 for all sessions using the forefoot. As before, the figure includes the correlation coefficients r_1 and r_2 which indicate the relation between the study period and the performance in test 1 for relative pitch and test 2 for absolute pitch, respectively. The coefficients are comparable to those for the fingertip, which indicates that the performance in both tests does not depend on the amount of study.

Between C3 and G3, the correct identification of absolute pitch was typically higher than the correct identification of relative pitch in most of the sessions, as with the results from the fingertip (cf. Tables 6.1 and 6.2). Between A3 to A4, the correct identification of relative pitch with the forefoot or the fingertip tended to be larger than for absolute pitch. However, C5 showed higher scores for the correct identification of absolute pitch using the forefoot.

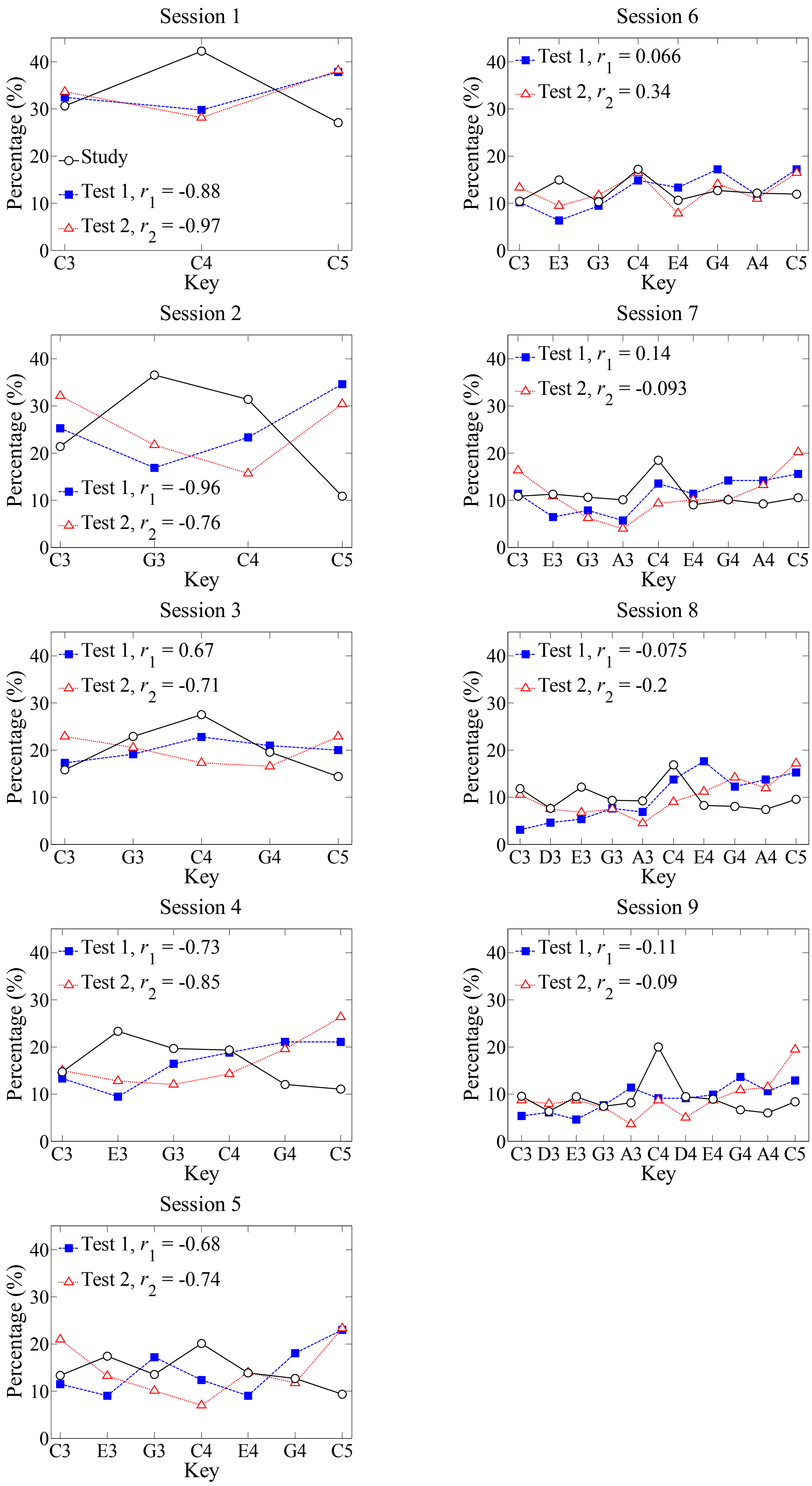

Figure 6.6 Total percentage of times that keys were pressed in the study (—○—) and mean percentage of correct responses in test 1 (—■—) and test 2 (···Δ···) using the forefoot (cf. Table 6.2).

Table 6.2 Percentage of times each key was pressed in the study period and the difference between test 1 (T1) for the identification of relative pitch and test 2 (T2) for the identification of absolute pitch in terms of the percentage of correct scores using the forefoot**.** Negative values are marked in bold font and indicate that the score in test 1 was lower than the score in test 2.

Forefoot session		C3	D3	E3	G3	A3	C4	D4	E4	G4	A4	C5
1	Study	30.65					42.23					27.11
	T1	32.43					29.73					37.84
	T2	33.64					28.18					38.18
	T1−T2	**−1.21**					1.55					−0.34
2	Study	21.33			36.51		31.38					10.77
	T1	25.23			16.82		23.36					34.58
	T2	32.17			21.74		15.65					30.43
	T1−T2	**−6.94**			**−4.92**		7.71					4.15
3	Study	15.76			22.85		27.48			19.55		14.36
	T1	17.27			19.09		22.73			20.91		20.00
	T2	22.83			20.47		17.32			16.53		22.85
	T1−T2	**−5.56**			**−1.38**		5.41			4.38		**−2.85**
4	Study	14.68		23.30	19.68		19.29			12.05		11.00
	T1	13.28		9.38	16.41		18.75			21.09		21.09
	T2	15.03		12.78	12.03		14.29			19.55		26.32
	T1−T2	**−1.75**		**−3.40**	4.38		4.46			1.54		**−5.23**
5	Study	13.27		17.37	13.55		20.05		13.78	12.70		9.28
	T1	11.48		9.02	17.21		12.30		9.02	18.03		22.95
	T2	20.93		13.18	10.07		6.98		13.95	11.63		23.26
	T1−T2	**−9.45**		**−4.16**	7.14		5.32		**−4.93**	6.40		**−0.31**
6	Study	10.40		14.89	10.30		17.18		10.64	12.64	12.10	11.86
	T1	10.16		6.25	9.38		14.84		13.28	17.19	11.72	17.19
	T2	13.28		9.38	11.72		16.41		7.81	14.06	10.94	16.41
	T1−T2	**−3.12**		**−3.13**	**−2.34**		**−1.57**		5.47	3.13	0.78	0.78
7	Study	10.87		11.21	10.58	10.11	18.46		8.98	10.03	9.23	10.54
	T1	11.35		6.38	7.80	5.67	13.48		11.35	14.18	14.18	15.60
	T2	16.28		10.85	6.20	3.88	9.30		10.08	10.08	13.18	20.16
	T1−T2	**−4.93**		**−4.47**	1.60	1.79	4.18		1.27	4.10	1.00	**−4.56**
8	Study	11.76	7.60	12.16	9.29	9.22	16.82		8.21	8.07	7.35	9.51
	T1	3.05	4.58	5.34	7.63	6.87	13.74		17.56	12.21	13.74	15.27
	T2	10.45	7.46	6.72	7.46	4.48	8.96		11.19	14.18	11.94	17.10
	T1−T2	**−7.4**	**−2.88**	**−1.38**	0.17	2.39	4.78		6.37	**−1.97**	1.80	**−1.83**
9	Study	9.49	6.31	9.46	7.38	8.14	20.00	9.43	8.83	6.65	5.96	8.36
	T1	5.30	6.06	4.55	7.58	11.36	9.09	9.09	9.85	13.64	10.61	12.88
	T2	8.63	7.91	8.63	7.19	3.60	8.63	5.04	8.63	10.79	11.51	19.42
	T1−T2	**−3.33**	**−1.85**	**−4.08**	0.39	7.76	0.46	4.05	1.22	2.85	**−0.9**	**−6.54**

As with the results from the fingertip, the reference C4 was the most studied tone by 8.9% on average when testing the forefoot, except for the second and the fourth sessions. As before, this did not seem to be of any particular help in the identification task. However, Figure 6.6 shows a marked trend of increasing accuracy in the identification of relative and absolute pitch in the octave between C4 and C5. This could be due to the onset and offset cues which increased in magnitude with increasing pitch and, perhaps, with increasing contactor size.

Compared with the correct identification for absolute pitch, the correct identification of C4 for relative pitch over the training sessions tended to be equal or lower with the fingertip and equal or higher with the forefoot. The correct identification of relative pitch for C5 with the forefoot was usually equal or lower than for absolute pitch. However the correct identification of relative pitch for C5 with the fingertip was usually equal or higher than for absolute pitch.

For both the forefoot and fingertip, correct identification of relative pitch was typically higher for pitches between A3 and C5 compared with absolute pitch. However, the correct identification of absolute pitch was typically higher for pitches between C3 and G3 compared with relative pitch.

6.4.2.3 Response change per semitone away from a new note

Comparing the forefoot and the fingertip, Figure 6.7 shows the mean change in the percentage of correct responses as a function of the interval distance in semitones between a newly introduced tone and the active tones in test sessions. Introducing new tones that were between five or less semitones away from the active tones in a session for the forefoot produced a similar confusion effect to that obtained for the fingertip in Section 6.4.1.3. The exception to this was for the interval of two semitones where this detrimental effect was reduced by almost a half, from −8.2% to −4.8%. This supports the results in Chapter 5 showing that the forefoot can be more accurate in the discrimination of relative pitch for small interval sizes such as two semitones.

As before, the response change due to the perceptual similarity of the available tones in the identification task typically improved with increasing interval distance. This also helps to explain the progressive decrease in correct responses as the number of training sessions increased, as shown in Figure 6.5 and in the next section for the comparison of tests 1 and 2 using the fingertip and the forefoot.

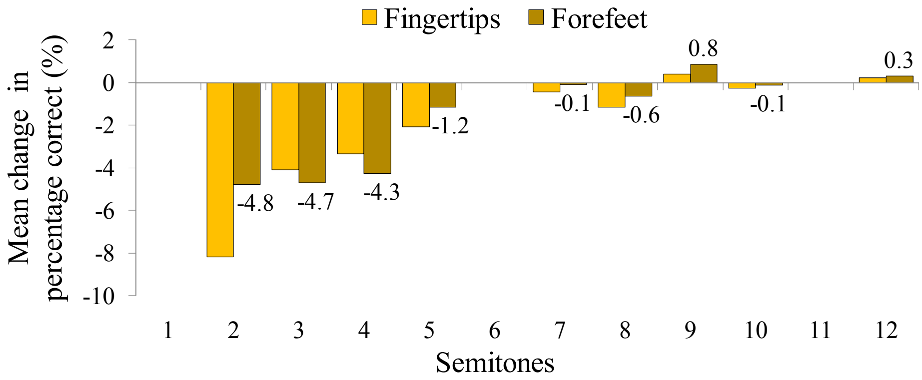

Figure 6.7 Mean change in the percentage of correct responses per semitone of distance away from a new tone using the forefoot. The interval distance on the *x*-axis indicates the number of semitones between the active test tones and a newly introduced test tone in a session. The pentatonic scale did not include interval distances of one, six and eleven semitones.

6.4.3 Comparison of tests 1 and 2 for fingertips and forefeet

When comparing tests 1 and 2 for fingertips and forefeet, the performance achieved with the forefoot for the first session was 14% lower compared with the performance with the fingertip (cf. Figures 6.2 and 6.5). As shown in Figure 6.8 and Table 6.3 for the results in test 1, there was a significant difference between the scores obtained from fingertips and feet for the first three sessions (independent t-test, $p < 0.05$). Similarly, for the results in test 2, there was a significant difference between the scores obtained from fingertips and forefeet for the first session only (independent t-test, $p < 0.05$).

These differences between hands and feet may be partly due to a higher motivation or ability from participants tested on fingertips that played a musical instrument and/or sang in a choir or vocal group to an academic or professional extent. In addition, half of these participants had absolute pitch which may have been advantageous in the tests. In contrast, approximately half of the participants tested on the forefoot played a musical instrument and/or sang in a choir or vocal group to an amateur extent; the other half of these participants had no musical skills and perhaps less motivation or ability during the tests. Nevertheless, the lower test performance with the forefoot would support the results from Chapter 5 that the forefeet were relatively less accurate in the discrimination of relative pitch.

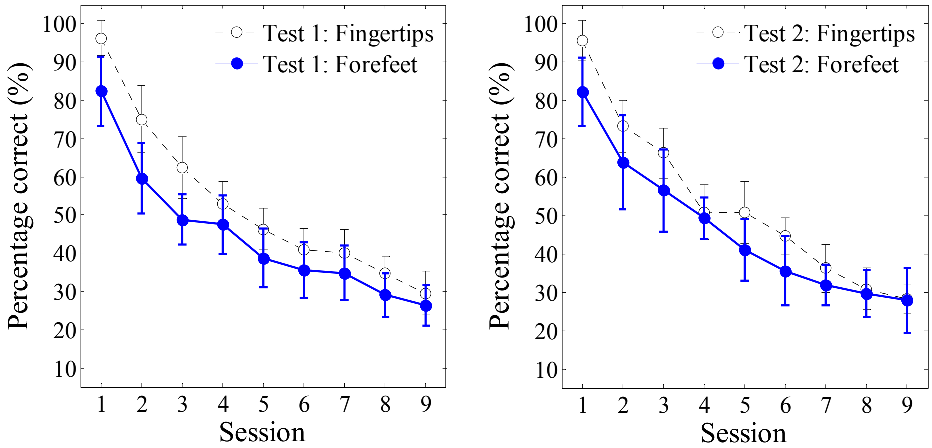

Figure 6.8 Mean percentage of correct responses for test 1 and test 2 using the middle fingertip and the forefoot. The error bar indicates the 95% confidence interval.

Table 6.3 Statistical results from the independent *t*-test to compare performance for the fingertip and the forefoot in tests 1 and 2.

Session	Test 1			Test 2		
	p	$t(31)$[a]	r	p	$t(31)$[a]	r
1	**0.005**	3.055	**0.481**	**0.008**	2.837	**0.454**
2	**0.015**	2.577	**0.420**	0.147	1.486	0.258
3	**0.011**	2.695	**0.436**	0.096	1.716	0.295
4	0.245	1.186	0.208	0.726	0.354	0.063
5	0.090	1.748	0.300	0.083	1.792	0.306
6	0.232	1.219	0.214	0.055	1.992	0.337
7	0.257	1.155	0.203	0.277	1.106	0.195
8	0.110	1.645	0.283	0.765	0.301	0.054
9	0.405	0.844	0.150	0.912	0.112	0.020

[a] Test statistic and degrees of freedom for the independent *t*-test.

Although these results provide further evidence to confirm the hypothesis that training had no effect on the identification of relative and absolute pitch, there were indications that the identification task can be improved.

6.5 Implications for Musical Performance

The results in this chapter have shown that pitch height is important to identify relative pitch which is learned by most musicians to recognise intervals, whilst absolute pitch is usually acquired by fewer people. The results from the present experiment have provided new insight into the identification of pitch height in the vibrotactile mode.

Section 6.4.2.3 has shown that the forefoot can identify the interval of two semitones (i.e. a whole tone) considerably better than the fingertip. This supports the findings in Chapter 5 which showed that forefeet can discern small-sized intervals significantly better than the fingertip. In addition, correct pitch identification was significantly better with the fingertip than the forefoot over the initial training sessions.

The results in Figure 6.6 showing increasing accuracy with increasing pitch between C4 (392Hz) and C5 (523.3Hz) in the identification tests using the forefoot would support the results from Chapter 4 showing that the forefoot showed increasing sensitivity compared with the fingertip from ≈C5. This effect could be partly due to the onset and offset of the notes that started to be progressively felt by participants using the fingertip as the pitch increased, although this was not tested with the forefoot. The ability to distinguish higher notes with the forefoot adds to the evidence that using a relatively large contactor has benefits in detecting pitch over a wide frequency range as well as being more practical for musical performance than the fingertip for most musicians.

Sections 6.4.1.3 and 6.4.2.3 showed that the perceptual similarity of interval sizes in the identification task decreased progressively for fingertips and forefeet until the tones were separated by seven semitones at which point the tones were typically perceived as distinct. As shown in Chapter 5, the post-training test of relative pitch discrimination showed that fingertips could discriminate significantly better larger intervals from nine to twelve semitones, whereas forefeet could discriminate significantly better the interval of one semitone. In agreement with the above results from Section 6.4.2.3, participants showed considerably more accuracy identifying the interval of two semitones when using the forefeet in the experiment.

To some extent, the results from the present experiment indicate that participants were able to identify relative and absolute pitch. However, participants did not learn as efficiently as expected even though the interval distances used were the same as in the previous experiment on relative pitch discrimination, except for one, six and eleven semitones. Moreover, participants did not learn well despite the favourable training results obtained in Chapter 5 to discriminate relative pitch with fingers or forefeet. With this particular training method, the amount of study was typically weakly correlated with the performance in the tests to identify pitch (see Sections 6.4.1.2 and 6.4.2.2). In addition, the number of choices presented was relatively large in single sessions. Verrillo and Gescheider [22] have noted that cognitive factors such as short-term memory, attention and pattern recognition can affect considerably the user performance of tactile communication systems.

Nevertheless, identification is more demanding than discrimination, although some participants with musical skills could have been more able than others to identify pitch correctly. It should be noted that the identification in the auditory domain is already challenging, especially for participants with normal hearing that have no absolute pitch, as reported by Miyazaki [216]. Moreover, for the identification of relative pitch, the reference tone C4 may have produced too much information to process perceptually before identifying the tone that followed the reference. Conversely, the repetition of the same tone in a pair in the test for absolute pitch was seemingly helpful to identify absolute pitch more directly, without the need to compare with a reference tone.

The high scores over the initial sessions in both training tests provide some indication that training could help achieve higher scores of accuracy in relative and absolute pitch identification. Thus, training could be developed adopting methods similar to those suggested by Plant [45].

By way of an example, a more successful training programme could focus on the four tones from the second session (i.e. C3, G3, C4 and C5) over two sessions (I and II) instead of a single session; session I would only include C3 and the newly introduced G3 which are both the closest tones to each other apart from C4 and hence relatively difficult to identify; session II would include the entire set of four tones (see highlighted keys in Figure 6.1). Subsequently, the five tones from the third session (i.e. C3, G3, C4, G4 and C5) could be similarly learned in two sessions as well; session I would only include C5 and the newly introduced G4 which are the new closest tones to each other; session II would include the entire set of five tones. This training routine would continue until all the required tones are completed. The number for the entire set of sessions would double from nine to eighteen, which would still be reasonable for such a demanding identification task.

In order to bring these results out of the laboratory, different types of music could be considered to suit the different degrees of accuracy in distinguishing musical intervals via the fingertip and the forefoot. Perhaps, a music scale could be adapted based on a minimum interval distance of two semitones (whole tones) to compose vibrotactile patterns using the vibrotactile score akin to a musical score as reported by Lee and Choi [217] and Lee *et al* [218].

6.6 SUMMARY

The experiment to measure pitch identification via fingertips and forefeet of participants with normal hearing involved nine training sessions each consisting of a preliminary study period followed by a test on relative pitch and another test on absolute pitch. The presentation of stimuli involved eleven tones using a pentatonic scale in the two-octave range C3 (130.81Hz) to C5 (523.25Hz) using the same suprathreshold level of stimuli described in Chapter 5.

Considering the favourable results from relative pitch discrimination in Chapter 5, the training results for the present experiment were lower than expected presumably due to the different nature of discrimination and identification tasks. The training tests produced relatively large scores in the correct identification of pitch for the first few sessions. However, as new tones were progressively added in subsequent sessions the performance decreased progressively.

The results showed that training had no effect on the identification of relative and absolute pitch (Wilcoxon, $p > 0.05$). Similarly, there was no significant difference between the correct identification of pitch with the fingertip and the forefoot for both training tests (independent t-test, $p > 0.05$), except for the three first sessions in the test for relative pitch identification and the first session in the test for absolute pitch identification; in both cases, identification was significantly better with fingertips. This has suggested that the identification task might be improved by developing a more involved training method at the expense of doubling the length of the training.

Regardless of using the fingertip or the forefoot, the amount of study of the tones and their correct identification in both tests were predominantly not correlated. However, these results indicated that the correct identification of relative pitch was typically higher for high pitch between A3 and C5 compared to the correct identification of absolute pitch which was higher for lower pitch between C3 and G3.

The reference tone C4 was generally the most studied note in both tests using the fingertip or the forefoot. However, this did not seem to be of any particular help in the identification task and indicated the need to improve the training method. However, there was a marked trend of increasing accuracy in the correct identification of relative and absolute pitch in the octave between C4 and C5 using the forefoot.

Introducing new tones up to five semitones away from the active tones in a training session produced a similar change in the participants' response using the fingertip or the forefoot. The exception to this was for the interval of two semitones where the detrimental change in the participants' response using the forefoot was reduced by almost half compared with the change produced when using the fingertip. This supported the results from Chapter 5 showing that the forefoot was more accurate in the discrimination of relative pitch for small interval sizes of one or two semitones.

Considering that relative pitch is more beneficial than absolute pitch for the majority of performing musicians, the above findings indicate that the perception of relative pitch with the forefoot compared with that with the fingertip would be enhanced when using intervals spanning up to approximately a whole tone with high pitch between approximately C4 and C5.

7 CONCLUSIONS

The vibrotactile perception of musical pitch has been accurately assessed with careful consideration of the associated perception of intensity and the transient parts of musical notes of 1s duration. Psychophysical experiments were designed for the fingertips of participants with normal hearing and with a hearing impairment as well as the forefoot and the heel of participants with normal hearing for training purposes.

Results were obtained through bespoke graphical user interfaces and vibration transmitters in the form of electromagnetic shakers with bespoke skin contactors which did not include a surround gap for practical purposes. In order to obtain reliable results, the vibrotactile sensation was dissociated from both pure-tone air conduction and bone conduction and the participants' type of hearing was also distinctly indicated.

7.1 DETECTION THRESHOLDS

In agreement with other studies [94-96], no significant difference (Mann-Whitney, $p > 0.05$) was found between the mean vibrotactile detection thresholds in terms of displacement for the middle fingertip of participants with normal hearing and with severe/profound hearing impairments over the range of musical notes from C1 (32.7Hz) to C6 (1046.5Hz). This was regardless of the occlusion of the ear canal by wearing hearing aids or in-ear headphones (sometimes used for stage monitoring by musicians with normal hearing), which would result in the take-up of vibrotactile cues by everyone.

Using a practical level of presentation ≈10dB above the mean detection threshold, an optimal and safe dynamic range in terms of frequency-weighted acceleration has been estimated to vary between 12 and 27dB over the three-octave range C2 (65.4Hz) to C5 (523.3Hz). This is in line with other studies [179, 182]. However, the dynamic range below G1 (49Hz) and above G5 (784Hz) is restrictive for some types of music and would require high vibration levels that would need careful consideration and perhaps compressing the dynamics of the signal in order to avoid adverse physiological effects. Moreover, sensory adaptation [84, 86, 87, 177] due to prolonged periods of exposure to vibrotactile stimuli and temporal summation [61] due to the usage of notes below 1s are also factors to be considered because they may vary the perception of detection thresholds.

Tests on the fingertips indicated that at and above A5 (880Hz), only the transient parts at the beginning and end of the notes were typically detected thus making the identification of pitch potentially difficult.

For participants with normal hearing and the specific contactor areas used in this experiment, a significantly lower mean detection threshold was found for the forefoot and the heel compared to the middle fingertip, except between G3 (196Hz) and C5 (523.3Hz) for the forefoot (Mann-Whitney, $p > 0.05$) and between C3 (130.8Hz) and C5 (523.3Hz) for the heel (independent t-test, $p > 0.05$). Therefore, the forefoot and the heel could use a similar dynamic range to the fingertip for this range of notes and yet a wide variety of fundamental frequencies of musical instruments.

7.2 DISCRIMINATION AND LEARNING OF RELATIVE PITCH

A suprathreshold level of 15dB for stimuli presentation between C3 (130.8Hz) to C5 (523.3Hz) allowed for headroom without affecting the perception of vibrotactile pitch in that range of maximum sensitivity [116]. For participants with normal hearing, although the correct discrimination of relative pitch before training using the middle fingertip tended to be higher compared with the forefoot, the difference was non-significant, except for the interval of six semitones (Mann-Whitney, $p < 0.05$). The comparison between participants with normal hearing and with severe/profound hearing impairments for correct discrimination in the pre-training test using the middle fingertip showed no significant difference (Mann-Whitney, $p > 0.05$).

During sixteen training sessions undertaken for five or six weeks, participants with normal hearing showed a clear trend of improvement in the correct discrimination of relative pitch in terms of interval size in semitones. Using the fingertip, the percentage of correct responses was $\geq 70\%$ for intervals of four to twelve semitones with or without training, whilst the same performance using the forefoot only happened after training. This indicates that short-term training is beneficial to improve the discrimination of relative pitch. An increasing performance between successive training sessions would be higher by improving the feedback given to the participants depending on the individual degrees of progress during the training rather than using a larger number of sessions.

Comparing pre- and post-training results, the correct discrimination of relative pitch with the fingertip was higher (Wilcoxon, $p < 0.05$) for intervals between nine and twelve semitones, whilst the correct discrimination of relative pitch with the forefoot was higher for the smaller intervals of one semitone (dependent *t*-test, $p = 0.05$) and three, five and six semitones (dependent *t*-test, $p < 0.05$). Therefore, single semitones or whole tones presented to the forefoot rather than the fingertip should enhance the perception of relative pitch in the range C3 (130.8Hz) to C5 (523.3Hz).

Furthermore, based on the finding from Chapter 4 that the forefoot is more sensitive than the fingertip below C3 and assuming a similar accuracy of the forefoot to discriminate the smallest interval sizes also for lower tones up to C2 (65.4Hz), the forefoot would also be more useful than the fingertip for the smallest interval sizes even at lower intensity levels. This would apply within the available practical dynamic range for music notes presented 10dB above threshold.

7.3 IDENTIFICATION AND LEARNING OF RELATIVE AND ABSOLUTE PITCH

This experiment used the same suprathreshold level and the similar range of notes with most of the interval distances already included in the previous experiment on relative pitch discrimination. However, the correct recognition of pitch was comparatively lower. The training for both tests in the identification of relative pitch (i.e. test 1) and absolute pitch (i.e. test 2) produced relatively high scores for correct identification for the first few sessions. However, the performance in the tests decreased progressively as new tones were progressively added during the nine training sessions undertaken for approximately four weeks.

This suggests that the identification task was considerably more demanding than the discrimination task and that the results might be improved by changing the training method. As suggested by Galvin *et al* [125], the new method would involve doubling the number of sessions due to the difficulty of the experiment and the variety of cognitive skills among the participants.

There was no significant difference (Wilcoxon, $p > 0.05$) between the test for the identification of relative pitch and the test for the identification of absolute pitch using the fingertip or the forefoot. However, there was a significant difference (independent t-test, $p < 0.05$) between the correct identification of pitch with the fingertip and with the forefoot for a few of the early sessions in both tests. This was another indication that the identification task might be improved by changing the training method.

When using the forefoot compared with the fingertip, the introduction of new notes that were only two semitones away from the active notes in a training session improved the percentage of correct responses by almost half. This would substantiate the finding from the previous experiment that the accuracy in relative pitch discrimination of small-sized intervals with the forefoot is higher compared with the fingertip.

Between C4 (261.6Hz) and C5 (523.3Hz), there was a marked trend of increasing accuracy in the identification of relative and absolute pitch using the forefoot only. This supports the results from the experiment on detection thresholds indicating that the forefoot was increasingly sensitive compared with the fingertip for notes above C5 with the specific contactor areas used for these experiments.

Overall, the findings in this thesis have been shown to be important for the development of learning through training and communication methods in order to enhance effectively the musical experience of people with a hearing impairment. As mentioned in the introduction of this thesis, proof of principle has been shown; three normal hearing musicians played together a well-known pop-rock song using vibrating footrests and standard musical instruments such as electric guitar, bass guitar and drum kit without any auditory feedback under controlled experimental conditions. Furthermore, the same principle would allow expanding the number of performing musicians with normal hearing and with a hearing impairment interacting with each other in a similar setting.

7.4 FUTURE RESEARCH

As indicated in the introduction section, the ideal setting for interactive performance for musicians with a hearing impairment would involve individual control of a musician's signal distributed over the main mix. For this purpose, machine learning techniques such as artificial neural networks [219] would be an option requiring input variables from the above experiments plus new experiments or training programmes suggested in this section. The design and analysis of the new experiments would also require further consideration of the participants' cognitive or musical skills as discussed in [125].

Following the results from the discrimination of relative pitch in Chapter 5, another ability to test would be the discrimination of vibrotactile music intervals or simple chords which helps to determine the notes in a melody as in aural recognition [220]. This would build on the results from Chapter 6 towards vibrotactile identification of melody.

Exploring the vibrotactile consonance of intervals as in [135] would also expand on the results from Chapter 5 where the discrimination of the interval of nine semitones using the fingertips showed a notable contrast compared with the forefoot. Vibrotactile dissonance may have affected adversely the performance of forefeet in the range of notes between A3 (220Hz) and D4 (293.7Hz), which represents almost half of the notes available to form the pairs of notes used in the interval of nine semitones.

In order to emulate more realistic signals, the recognition of simple vibrotactile synthetic chords could be investigated using time-varying factors as in [119]. However, vibration containing a relatively broad band of frequencies or notes of relatively short duration should be carefully considered in order to control sensory adaptation [22, 85] and temporal summation [22, 61], which may affect the detection thresholds and the discrimination and identification of vibrotactile pitch.

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APPENDIX A: APPARATUS AND EXPERIMENTAL SET-UPS

Data corresponding to Chapter 3 are included in this Appendix. Tables A.1 and A.2 show the reference levels used for the calibration procedure followed before and after each test session in order to obtain personalised measurements on the forefoot or the heel of each participant.

Table A.1 Reference levels of test tones used for the forefoot disc.

Note	C1	G1	C2	G2	C3	G3	C4	G4	C5	G5	C6
Level, dBVrms	−6.20	8.42	8.03	1.75	0.49	−1.67	−1.97	−3.04	−3.35	−1.78	−2.41

Table A.2 Reference levels of test tones used for the heel disc.

Note	C1	G1	C2	G2	C3	G3	C4	G4	C5	G5	C6
Level, dBVrms	−6.17	6.78	10.28	3.25	1.38	0.21	−0.89	−2.01	−2.33	−0.21	−2.07

As explained in Section 3.3.1.1.F, the effect of pressing down with the foot on the contactor discs was measured in order to establish the effect that this would have in the measurement of detection thresholds. The difference in acceleration levels due to pressing lightly compared to without placing the foot on the disc was found to be significant at some test tones.

Table A.3 shows the measurements taken for one volunteer with foot size (UK) 9, weight 90kg and height 1.76m prior to establishing the above reference levels (see Tables A.1 and A.2). The change in level in the synthesised test tones made the level at the contactor discs change approximately the same amount, except for the error magnitudes ≥ 1dBVrms marked in bold font in Table A.3. Therefore, post-hoc compensation on these values was needed. Note that the missing levels for the heel disc were not needed because previous ad-hoc tests established that these levels were relatively linear between G3 and C6.

Table A.3 Acceleration measured in dBVrms (re: 1Vrms) for the loading of the forefoot (top table) and the heel (bottom table) for five different levels of test tones described in dBV (re: 1V). Error magnitudes ≥ 1dBVrms are marked in bold type.

Forefoot	0dBV			−10dBV				−20dBV				−30dBV				−40dBV			
Note	Unload*	Load	Change[a] U*−L	Unload	Load	Change[b] U−U*	Change[c] U−L	Unload	Load	Change[b] U−U*	Change[c] U−L	Unload	Load	Change[b] U−U*	Change[c] U−L	Unload	Load	Change[b] U−U*	Change[c] U−L
C1	−6.16	−7.10	0.94	−16.08	−16.82	−9.92	0.74	−26.04	−27.14	−19.88	**1.10**	−36.04	−37.18	−29.88	**1.14**	−46.07	−47.34	−39.91	**1.27**
G1	8.35	3.50	**4.85**	−1.66	−8.36	−10.01	**6.70**	−11.69	−18.82	−20.04	**7.13**	−21.68	−28.99	−30.03	**7.31**	−31.00	−39.03	−39.35	**8.03**
C2	8.16	6.50	**1.66**	−1.68	−8.20	−9.84	**6.52**	−11.61	−19.22	−19.77	**7.61**	−21.60	−29.30	−29.76	**7.70**	−31.60	−39.59	−39.76	**7.99**
G2	1.87	1.50	0.37	−8.01	−8.32	−9.88	0.31	−17.93	−18.32	−19.80	0.39	−27.92	−27.75	−29.79	−0.17	−37.93	−37.81	−39.80	−0.12
C3	0.45	0.33	0.12	−9.41	−9.50	−9.86	0.09	−19.34	−19.53	−19.79	0.19	−29.32	−29.43	−29.77	0.11	−39.33	−39.45	−39.78	0.12
G3	−1.22	−1.71	0.49	−11.1	−10.95	−9.88	−0.15	−21.09	−20.86	−19.87	−0.23	−31.03	−30.81	−29.81	−0.22	−40.98	−40.78	−39.76	−0.20
C4	−1.79	−2.07	0.28	−11.64	−11.95	−9.85	0.31	−21.57	−21.88	−19.78	0.31	−31.56	−31.87	−29.77	0.31	−41.57	−41.84	−39.78	0.27
G4	−2.91	−3.3	0.39	−12.76	−13.19	−9.85	0.43	−22.70	−23.08	−19.79	0.38	−32.68	−33.07	−29.77	0.39	−42.69	−43.07	−39.78	0.38
C5	−3.27	−3.87	0.60	−13.14	−13.86	−9.87	0.72	−23.08	−23.82	−19.81	0.74	−33.07	−33.81	−29.80	0.74	−43.08	−43.79	−39.81	0.71
G5	−1.98	−1.04	−0.94	−11.82	−11.32	−9.84	−0.50	−21.76	−21.25	−19.78	−0.51	−31.75	−31.24	−29.77	−0.51	−41.75	−41.24	−39.77	−0.51
C6	−2.69	−2.07	−0.62	−12.56	−12.45	−9.87	−0.11	−22.50	−22.40	−19.81	−0.10	−32.50	−32.39	−29.81	−0.11	−42.51	−42.39	−39.82	−0.12

Heel	0dBV			−10dBV				−20dBV				−30dBV				−40dBV			
Note	Unload*	Load	Change[a] U*−L	Unload	Load	Change[b] U−U*	Change[c] U−L	Unload	Load	Change[b] U−U*	Change[c] U−L	Unload	Load	Change[b] U−U*	Change[c] U−L	Unload	Load	Change[b] U−U*	Change[c] U−L
C1	−6.33	−16.10	**9.77**	−16.5	−27.16	−10.17	**10.66**	−26.65	−37.38	−20.32	**10.73**	−36.65	−47.46	−30.32	**10.81**	−46.67	−57.53	−40.34	**10.86**
G1	6.64	−9.25	**15.89**	−3.49	−19.54	−10.13	**16.05**	−13.55	−29.82	−20.19	**16.27**	−23.57	−39.70	−30.21	**16.13**	−33.60	−49.15	−40.24	**15.55**
C2	10.17	0.50	**9.67**	0.11	−12.12	−10.06	**12.23**	−9.91	−22.45	−20.08	**12.54**	−19.91	−32.71	−30.08	**12.8**	−29.92	−42.84	−40.09	**12.92**
G2	3.15	5.30	**−2.15**	−7.01	−3.89	−10.16	**−3.12**	−17.09	−13.93	−20.24	**−3.16**	−27.11	−29.14	−30.26	**2.03**	−37.13	−33.98	−40.28	**−3.15**
C3	1.26	2.00	**−0.74**	−8.90	−7.32	−10.16	**−1.58**	−18.96	−17.28	−20.22	**−1.68**	−29.00	−27.31	−30.26	**−1.69**	−38.99	−37.37	−40.25	**−1.62**
G3	0.10	−0.33	0.43	−10.02	−10.23	−10.12	0.21	−20.05	−20.28	−20.15	0.23	−30.06	−30.36	−30.16	0.30	−40.08	−40.35	−40.18	0.27
C4	−1.01	−1.25		−11.10		−10.09		−21.14		−20.13		−31.14		−30.13		−41.13		−40.12	
G4	−2.16	−2.52		−12.25		−10.09		−22.27		−20.11		−32.27		−30.11		−42.27		−40.11	
C5	−2.56	−2.86		−12.64		−10.08		−22.65		−20.09		−32.65		−30.09		−42.67		−40.11	
G5	−1.25	−1.24		−11.37		−10.12		−21.39		−20.14		−31.38		−30.13		−41.38		−40.13	
C6	−2.13	−5.10		−12.22		−10.09		−22.23		−20.10		−33.22		−31.09		−42.24		−40.11	

[a] Difference in dBVrms between levels measured without the foot on the disc (Unload*) and with the foot on the disc (Load) for the maximum level of 0dBV.

[b] Decrease in dBVrms from the Unload* level which used the maximum level of 0dBV. Expected decreases were −10, −20, −30 or −40dBVrms.

[c] Difference in dBVrms between levels measured without the foot on the disc and with the foot on the disc for the decreased level described in dBV.

APPENDIX B: ESTABLISHING DETECTION THRESHOLDS

For Chapter 4, this appendix includes Section B.1 for research ethics and scripts for participants and Section B.2 for subjective measurements.

B.1 RESEARCH ETHICS AND SCRIPTS FOR PARTICIPANTS

The following subsections are included below for the setup to measure on fingertips: B.1.1 recruitment advertisement, B.1.2 information sheet, B.1.3 consent form, B.1.4 questionnaire, and B.1.5 script for participants. The script for participants was adapted from the experimental set-up for the fingertip to the experimental set-up for the foot.

B.1.1. Recruitment advertisement

Below is the advertisement to recruit volunteers.

16 October 2012 Version 2

Recruitment advert

Volunteers needed for research into vibrotactile perception of music

The Acoustics Research Unit at the University of Liverpool are seeking healthy adult volunteers with or without a hearing impairment for a new research project. The project is investigating new ways to assist musicians with a hearing impairment when they play music with other musicians by making use of tactile perception of music in the form of vibration.

The two main aims of the research are:

(1) to understand how musicians with hearing impairments rehearse and perform music together, and with non-hearing impaired musicians, and

(2) to find a technological solution using vibration signals that will facilitate interactive group performance for hearing-impaired musicians.

The experiment in which you are being invited to participate is being used to determine:

(a) the lowest levels of vibration that can be felt by the fingers and feet, and

(b) the upper limit of comfort for vibration signals.

The results of this experiment will be used to help establish the lowest vibration levels at which it is possible to perceive musical notes using vibration, and the range of vibration levels which are considered comfortable. The tests will take place in the Acoustics Research Unit at the University of Liverpool and may take up to 1.5 hours.

Eligibility: Age range: 18 to 70 years; Gender, Ethnicity and Race: All
Other: No impairment in the feeling or sensation in hands and feet.

If requested and confirmed by us beforehand, we can pay reasonable travelling costs for participants who have travelled to Liverpool from outside of Merseyside specifically for this study. You will be paid £10 for participating.

The research is funded by the Arts and Humanities Research Council (AHRC). This experiment is being carried out by the Acoustics Research Unit at the University of Liverpool in collaboration with the Royal Northern College of Music.

Contact details: Please contact Mr Saúl Maté-Cid (Postgraduate Research Assistant, Acoustics Research Unit) by email at **saulmate@liv.ac.uk**

University of Liverpool Ethics Reference No. RETH000421

B.1.2 Information sheet

The below information was provided to participants before their sessions.

16 October 2012 Version 2

Information sheet

Research project: Interactive performance for musicians with a hearing impairment – Part 1: Tactometry

Researchers: Dr Carl Hopkins and Mr Saúl Maté-Cid

You are being invited to participate in a research study. Before you decide whether to participate, it is important for you to understand why the research is being done and what it involves. Please read the following information carefully and feel free to ask us if you would like more information or if there is anything that you do not understand. Feel free to discuss this with anyone else if you wish.

You do not have to accept this invitation and should only agree to take part if you want to.

We are grateful to you for considering this invitation.

What is the purpose of the study?

This research project is investigating new ways to assist musicians with a hearing impairment when they play music with other musicians by making use of tactile perception of music in the form of vibration.

The two main aims of the research project are:

(1) to understand how musicians with hearing impairments rehearse and perform music together, and with non-hearing impaired musicians, and

(2) to find a technological solution using vibration signals that will facilitate interactive group performance for hearing impaired musicians.

The experiment in which you are being invited to participate is being used to determine

(a) the lowest levels of vibration that can be felt by the fingers and feet

(b) the upper limit of comfort for vibration signals.

The results of this experiment will be used to help establish the lowest vibration levels at which it is possible to perceive music using vibration and the range of vibration levels which are considered comfortable.

Who is funding the research?

Arts and Humanities Research Council (AHRC) – Project ID: AH/H008926/1.

Why have I been chosen to take part?

We have approached adults with and without a hearing impairment to take part in this study.

Do I have to take part?

Participation is entirely voluntary and you are free to withdraw at any time.

What will happen if I take part?

You will be invited to sit by yourself in a quiet room in the Acoustics Research Unit so that you can focus on the experiment undisturbed. If for any reason during the experiment you need to leave the room, you can do so of your own free will. The room is monitored using a close-circuit video camera but it is not able to record images. It is used by the operator purely to monitor progress during the experiment.

You will be asked to place your fingertip on top of a smooth plate. This plate will then vibrate at a specific musical note. As soon as you feel the vibration tone, you press a button with your free hand. Once we have finished testing the fingertips on each hand, the process will be repeated using bare feet instead of fingertips.

Will you pay expenses?

If requested, we will pay reasonable travelling costs for participants who have travelled to Liverpool from outside of Merseyside specifically for this study. Please keep your receipts for bus/train tickets and we will arrange for you to be reimbursed.

You will be paid £10 for carrying out the experiment.

Are there any risks in taking part?

The vibration levels are low and are applied for a very short time, hence there are no known risks relating to human exposure to vibration in this experiment.

We will use an antibacterial cleaner on all contact surfaces for fingers and feet before and after each test.

Are there any benefits in taking part?

We hope that you will find it interesting to participate in this experiment. The main benefit is that you will be contributing to a body of research knowledge which is ultimately intended to help more people with a hearing-impairment to become musicians and to become involved in musical performances with other musicians.

What will happen to the results of the study?

The numerical results of the study will be published in conference and journal papers.

Will my participation be kept confidential?

The information you have given us will be securely stored. We will not include your name or personal details in materials being published or made available to researchers.

Will my taking part be covered by an insurance scheme?

Participants taking part in this University of Liverpool ethically-approved study will have cover.

What will happen if I want to stop taking part?

You can withdraw at any time, without explanation. Any information you give us up to that point may be used if you are happy for this to be done. Otherwise you may request that it is destroyed and no further use is made of it.

Who can I contact if I have further questions?

The contact details for the Principal Investigator on this project are:

Dr Carl Hopkins
Acoustics Research Unit, School of Architecture
Abercromby Square, University of Liverpool, Liverpool L69 7ZN

Office: 0151 794 4938
Email: carl.hopkins@liv.ac.uk

B.1.3 Consent form

The below form was completed by participants before their sessions.

06 January 2011 Version 2

UNIVERSITY OF LIVERPOOL

CONSENT FORM

Title of Research Project:	Interactive performance for musicians with a hearing impairment – Part 1: Tactometry
Researcher(s):	Dr Carl Hopkins and Mr Saúl Maté-Cid

		Please initial box
1	I confirm that I have read and have understood the information sheet dated 2 December 2010 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	☐
2	I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my rights being affected.	☐
3	I understand that, under the Data Protection Act, I can at any time ask for access to the information I provide and I can also request the destruction of that information if I wish.	☐
4	I agree to take part in the above study.	☐

Participant Name	Date	Signature
Name of Person taking consent	Date	Signature
Researcher	Date	Signature

The contact details of lead Researcher (Principal Investigator) are:

Dr Carl Hopkins, Acoustics Research Unit, School of Architecture
Abercromby Square, University of Liverpool, Liverpool L69 7ZN

Office: 0151 794 4938
Email: carl.hopkins@liv.ac.uk

B.1.4 Questionnaire

The below questionnaire was completed by participants before their sessions.

QUESTIONNAIRE

Name: ....

Email address: ....

Date of birth: ………………….. MALE ☐ FEMALE ☐

RIGHT-HANDED ☐ LEFT-HANDED ☐ AMBIDEXTROUS ☐

Hearing-impairment/deafness

Are you deaf/hearing impaired? YES ☐ NO ☐
(If No, go to the section "Musical Background")

a) Please indicate the level of deafness*?
Right ear: MILD ☐ MODERATE ☐ SEVERE ☐ PROFOUND ☐
Left ear: MILD ☐ MODERATE ☐ SEVERE ☐ PROFOUND ☐
(* Descriptions used by the RNID)

b) How old were you (in years) when you started to lose your hearing?
Right ear: 0-9 ☐ 10-19 ☐ 20-29 ☐ 30-39 ☐ 40-49 ☐ 50-59 ☐ 60-69 ☐ 70-79
Left ear: 0-9 ☐ 10-19 ☐ 20-29 ☐ 30-39 ☐ 40-49 ☐ 50-59 ☐ 60-69 ☐ 70-79

c) Do you use a hearing-aid? Right ear: YES ☐ NO ☐
Left ear: YES ☐ NO ☐

d) Do you currently experience tinnitus? YES ☐ NO ☐

Musical Background

Do you play a musical instrument and/or sing in a choir or vocal group?
YES ☐ NO ☐

If Yes,

a) What type of hearing aid do you wear when playing and/or singing?
Right ear: DIGITAL ☐ ANALOGUE ☐ NONE ☐
Left ear: DIGITAL ☐ ANALOGUE ☐ NONE ☐

b) What instrument(s) do you play?

c) How long have you been playing and/or singing? (in years)

d) Do you currently play and/or sing regularly (i.e. daily or weekly)?
YES ☐ NO ☐

e) Are you a professional musician**? YES ☐ NO ☐
(*** Definition: One who earns money from music-making*)

f) Do you have any qualifications in music? YES ☐ NO ☐
If yes, what is your highest qualification in music?
(E.g. ABRSM exam, degree/diploma)

g) Can you read music? YES ☐ NO ☐

As indicated in Section 4.2.1, Table B.1 defines the types of hearing loss according to the charity Action on Hearing Loss [2] (formerly known as the Royal National Institute for the Deaf). The hearing loss is measured by finding the quietest frequencies someone can just hear. This is called the threshold level and is measured in dB HL, where HL stands for "hearing level". Thresholds between 0 and 20dB HL across all frequencies measured indicate "normal" hearing [159].

Table B.1 Hearing loss defined by threshold.

Hearing loss	Threshold, dB HL	Description
Mild	25-39	Can sometimes make following speech difficult, particularly in noisy environments
Moderate	40-69	Makes following speech difficult without hearing aids
Severe	70-94	Usually implies the need to lipread or use sign language, even with hearing aids
Profound	95+	Usually implies the need to lipread or use sign language

B.1.5 Script

The below script was given to the participants to instruct them on how to proceed.

EXPERIMENT 'A' – PREPARATION FOR THE PARTICIPANT

As you read through the instructions below, please ask if you need any clarification.

Experimental procedure

- We are measuring the lowest levels at which you feel vibration using the *middle* finger of each hand.

- We will use 11 short vibration tones that are equivalent to musical notes found on the piano.

- Each 1-second tone will be played (i.e. *on*) followed by a 2-second interval with no tone (i.e. *off*) so that the tone will be played 3 times in a row (i.e. ***on,*** *off,* **on**, *off,* ***on,*** *off*).

Instructions (inside the booth)

- Please switch off your electronic mobile devices.

- Please do not consume food or drink inside the booth.

- Please remove any jewellery from the middle finger of each hand – a closable box is provided for this purpose and will be kept in front of you on the table during the test.

- Please be careful with your feet and knees so that they do not knock the equipment underneath the table.

- Make sure that you are sitting comfortably in the chair (adjust height) and maintain an upright posture. Try not to slouch or lean with your elbow on the table!). (*Demonstration*)

- Please try to avoid unnecessary movement of your body during the test.

- It is important that you remain comfortable during the test. If your fingers or hand feel uncomfortable or cold, please stretch or rub them together. We are able to see if you move your hand, and you will not interrupt the test. (*Demonstration*)

- The metal disc and the button will now be cleaned.

- Please place the fingertip of your middle finger *flat* on the metal disc. The middle part of your fingerprint should be gently placed in the middle of the disc. (*Demonstration*)

- Please ensure that you only touch the metal disc and NOT the black box around it. Also, please place your other hand and arm either on the black cloth or on your lap.

- As soon as you feel a tone or disturbance on the metal disc, press the button with your free hand. Try to press the button in time with the tones, for 1 second each time. Don't worry if you can't feel all 3 tones! The important thing is that you only press the button when you're sure that you feel a tone or disturbance on the metal disc. Note that there may be rather long time periods where you may not feel any tone at all. (*Demonstration using PowerPoint*)

- For your comfort, we will make a regular short break after approximately 20 minutes of testing.

- We will play noise through the loudspeakers continuously during the test. (*Demonstration*)

- We will be monitoring (but not recording) the test through the video camera in front of you.

- We will provide feedback on the test through the monitor in front of you.

- If you feel uncomfortable at any time, please stop the test by simply leaving the booth. (*Demonstration*)

- For users of hearing aids, we would ideally like you to remove them if you feel comfortable and if it is feasible. Whether you decide to remove the hearing aids or leave them in during the test, please make sure that there is consistency throughout the test (i.e. please don't remove the hearing aids once the test has started). Please inform the test operator now about your decision to wear (or not wear) hearing-aids.

- Now ensure that you place your middle finger correctly on the metal disc to start the test. (Noise is on).

B.2 SUBJECTIVE MEASUREMENTS

The following subsections for the setup to measure on fingertips are included: B.2.1 includes diagrams for the procedure to measure thresholds; B.2.2 includes the file contents output from the graphical user interface (GUI); and B.2.3 includes diagrams for the modified procedure to measure thresholds to test the perception of transient and continuous parts of test tones.

B.2.1 Diagram for measurement procedure

As explained in Section 4.3.1.2.A, the flowchart representing the procedure to measure detection thresholds on fingertips, forefeet and heels is shown below. Figures of the GUI panels are also included.

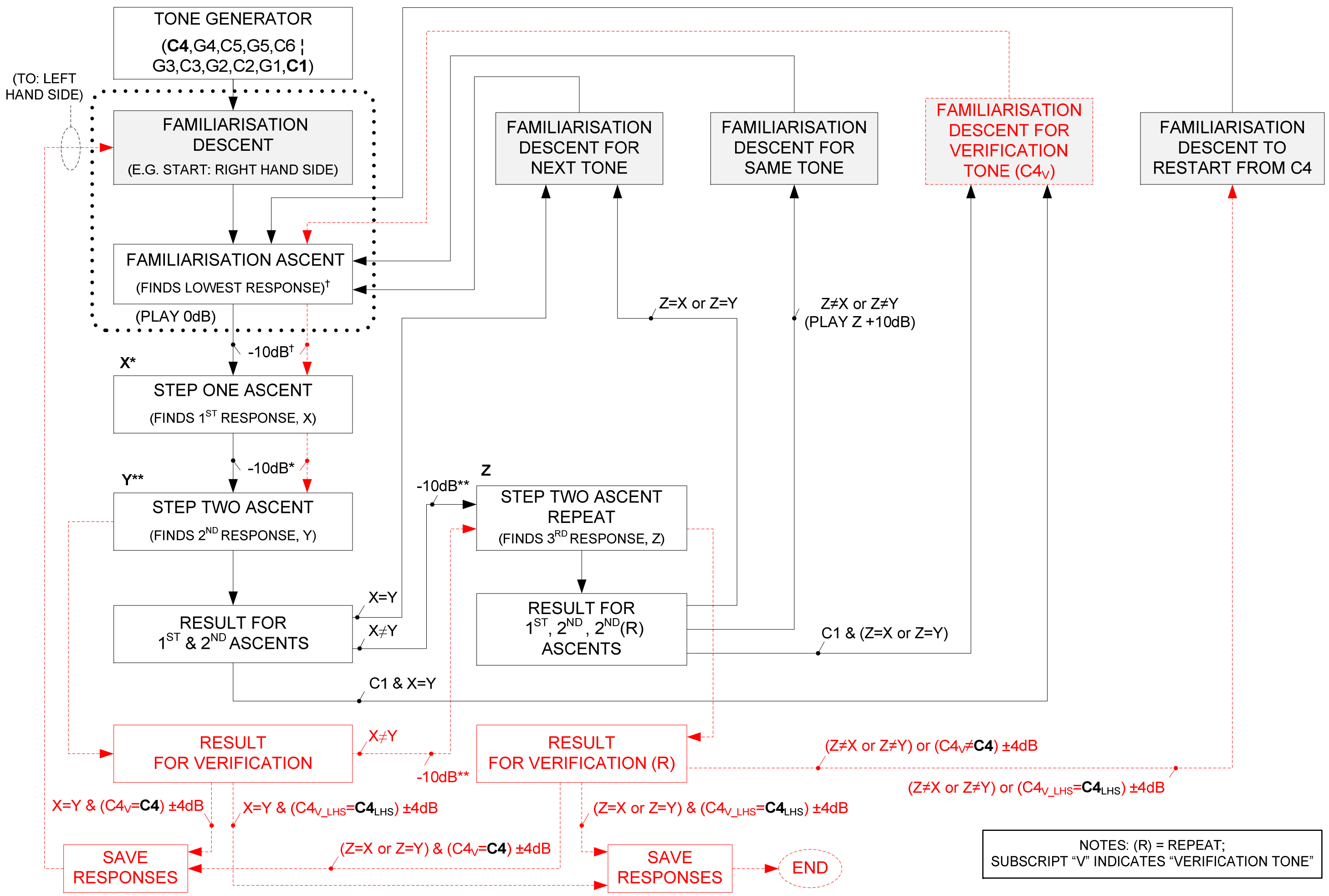

Figure B.1 Flowchart representing the procedure to measure detection thresholds on fingertips, forefeet and heels.

As explained in Section 4.3.1.2.A, Figures B.2 and B.3 are the panels of the GUI which was controlled by the experimenter and provided an automatic presentation of the stimuli to the participants.

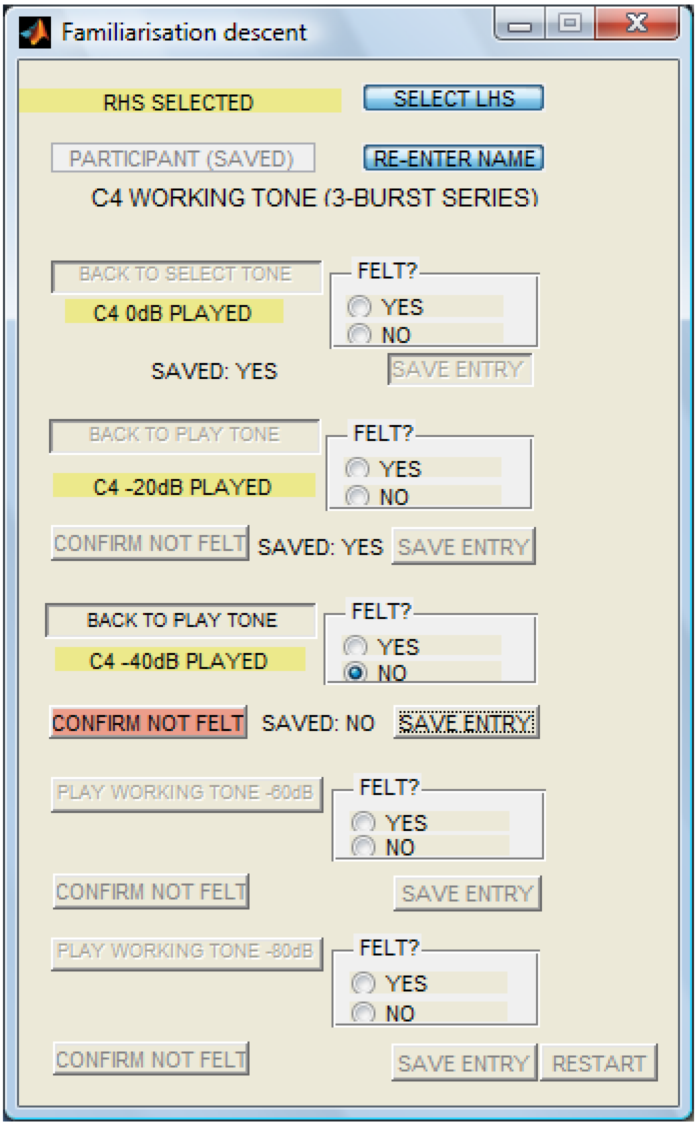

Figure B.2 GUI panel used for the initial familiarisation stage.

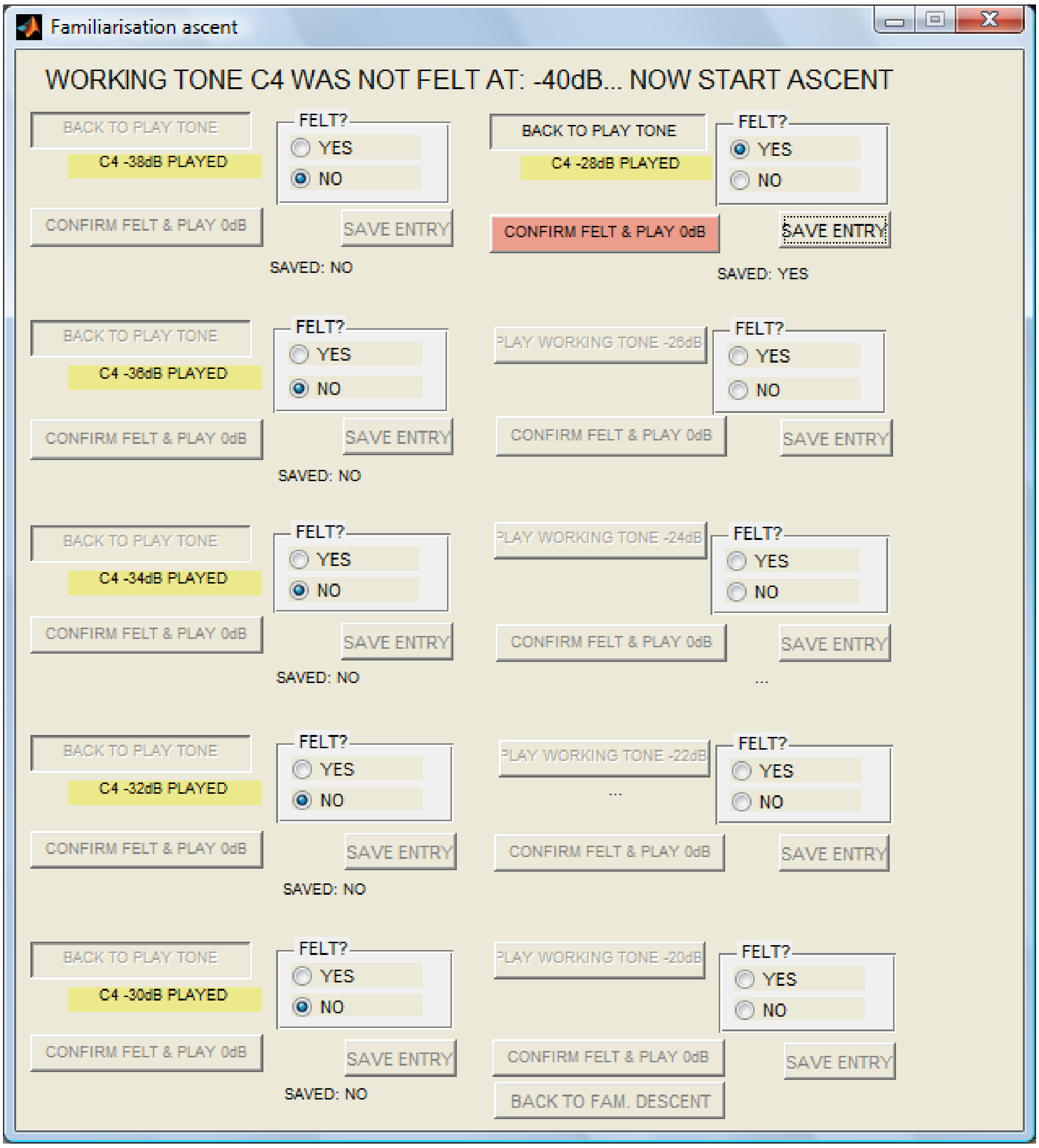

Figure B.3 GUI panel used for the familiarisation ascent.

B.2.2 Results output from GUI

Below is an example of the file contents output from the GUI, which shows raw data collected before and after a subjective test session using the fingertip. The section *calibration values* on the top shows the measured values for the test tones at reference level 0dBV and their corresponding acceleration before starting the test session (cf. Section 3.2.1.1). These values were obtained before arrival of the participant to start the subjective test session. The section *test results* on the bottom shows the values measured having finished the subjective test session for the participant's right hand.

***

Measured calibrator output (ideal: 10 ms^{-2}), dBVrms: −19.930
Correction factor to give 10 ms^{-2}: 0.9919733392

Note number, ascending from 1 (C1) to 11 (C6)

CALIBRATION VALUES FOLLOW:
****

Note #	dBVrms	Acceleration, ms^{-2} rms
1	−7.10	43.80
2	−3.89	63.39
3	−4.62	58.28
4	−5.69	51.52
5	−5.74	51.23
6	−5.59	52.12
7	−6.32	47.92
8	−7.26	43.00
9	−7.74	40.69
10	−8.06	39.22
11	−8.89	35.65

TEST RESULTS FOR RHS FOLLOW:
****

Note #	Test responses, dBV	Acceleration, ms^{-2} rms
1	−42.00	0.3479
2	−50.00	0.2004
3	−56.00	0.09236
4	−60.00	0.05152
5	−60.00	0.05123
6	−62.00	0.0414
7	−56.00	0.07595
8	−44.00	0.2713
9	−34.00	0.8119
10	−20.00	3.922
11	−8.00	14.19

Below is an example of the file contents output from the GUI, which shows raw data collected before and after a subjective test session using the forefoot including post−hoc compensation for individual, personalised measurements.

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Measured calibrator output (ideal: 10 ms^{-2}), dBVrms: 0.030
Correction factor to give 10 ms^{-2}: 0.9965520801

CALIBRATION VALUES FOLLOW:
****

Note #	dBVrms	Acceleration, ms^{-2} rms
1	−6.36	4.79
2	8.29	25.88
3	7.87	24.66
4	1.66	12.06
5	0.41	10.45
6	−1.72	8.18
7	−1.40	8.48
8	−3.27	6.84
9	−3.50	6.66
10	−1.81	8.09
11	−2.32	7.63

TEST RESULTS FOR RHS FOLLOW (NON−COMPENSATED):
****

Note #	Test responses, dBV	Acceleration, ms^{-2} rms
1	−32.00	0.1204
2	−44.00	0.1633
3	−50.00	0.07798
4	−52.00	0.0303
5	−48.00	0.04159
6	−42.00	0.06494
7	−28.00	0.3377
8	−16.00	1.084
9	−14.00	1.329
10	−6.00	4.055
11	−6.00	3.824

TEST RESULTS FOR RHS FOLLOW (COMPENSATED):
****

Note #	Test responses, dBV	Acceleration, ms^{-2} rms
1	−33.13	0.1057
2	−49.84	0.08337
3	−57.34	0.0335
4	−52.00	0.0303
5	−48.00	0.04159
6	−42.00	0.06494
7	−28.00	0.3377
8	−16.00	1.084
9	−14.00	1.329
10	−6.00	4.055
11	−6.00	3.824

B.2.3 Variation of measurement procedure

As explained in Section 4.3.1.2.C, Figure B.4 is the panel of the GUI that was used for recording answers from participants once the threshold had been determined for a tone, after stage 2 in the measurement procedure (see Section 4.3.1.2.A).

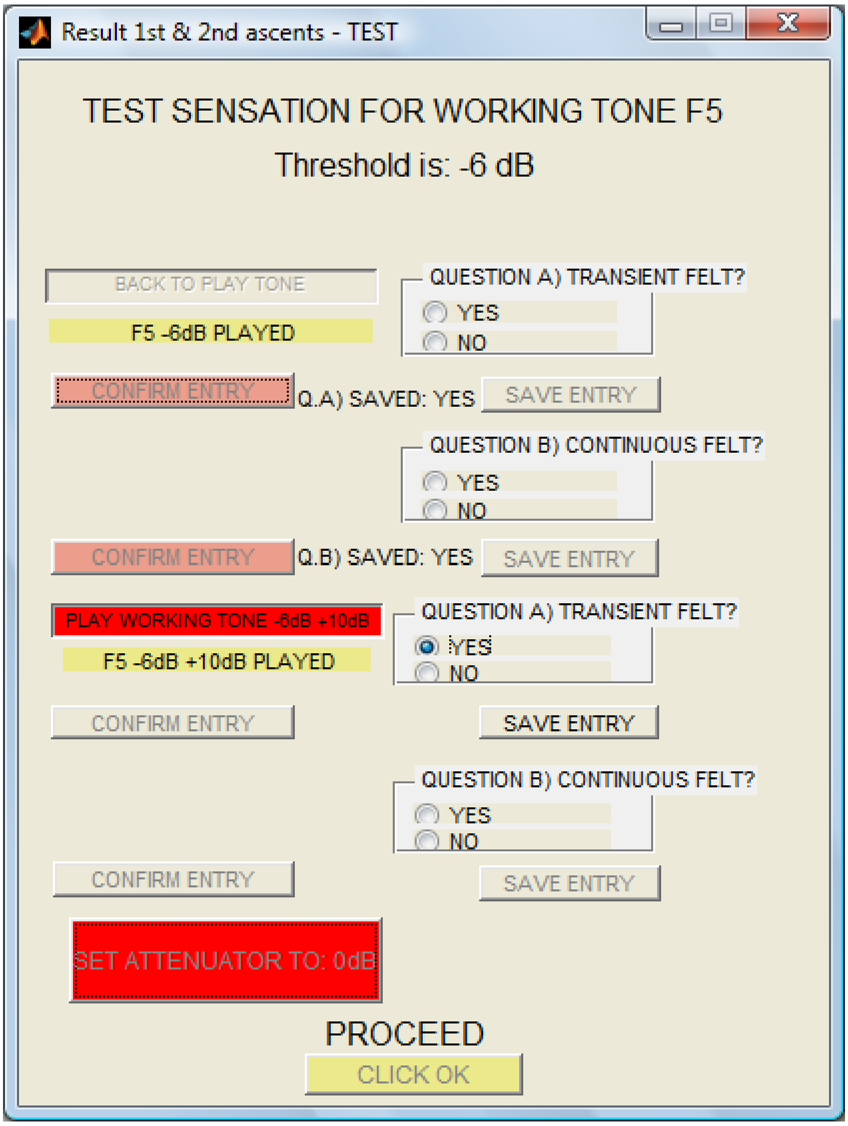

Figure B.4 GUI panel used to present suprathreshold levels and record answers from participants after determining the threshold for a tone.

APPENDIX C: RELATIVE PITCH DISCRIMINATION

This appendix for Chapter 5 includes the following sections: C.1 Objective measurements, C.2 Research ethics and scripts for participants and C.3 Subjective measurements.

C.1 OBJECTIVE MEASUREMENTS

As indicated in Section 5.3.1, Table C.1 includes the entire set of estimated values to obtain constant sensation at suprathreshold level across the required range of test tones. The error ratio between both measured and calculated accelerations was < 0.5dB in order to validate the estimated level of presentation of stimuli.

Table C.1 Reference values to produce constant sensation at suprathreshold level.

Note	Frequency, Hz	Estimated level, dBV (re: 1V)	Measured acceleration, ms^{-2} rms	Calculated acceleration, ms^{-2} rms	Error, dB (re: 1 ms^{-2})
C3	130.81	−37.00	0.71	0.71	0.00
C#3	138.59	−36.80	0.79	0.80	−0.10
D3	146.83	−34.70	0.89	0.89	0.00
D#3	155.56	−33.90	0.99	1.01	−0.20
E3	164.81	−34.00	1.12	1.13	−0.10
F3	174.61	−32.60	1.26	1.27	−0.10
F#3	185.00	−32.00	1.43	1.42	0.10
G3	196.00	−31.00	1.56	1.59	−0.20
G#3	207.65	−30.00	1.76	1.79	−0.10
A3	220.00	−29.00	1.98	2.01	−0.10
Bb3	233.08	−26.50	2.26	2.26	0.00
B3	246.94	−25.50	2.55	2.53	0.10
C4	261.63	−25.00	2.85	2.84	0.00
C#4	277.18	−24.00	3.23	3.19	0.10
D4	293.66	−23.00	3.72	3.58	0.30
D#4	311.13	−22.00	4.10	4.02	0.20
E4	329.63	−20.60	4.52	4.51	0.00
F4	349.23	−19.00	5.12	5.06	0.10
F#4	369.99	−18.50	5.90	5.68	0.30
G4	392.00	−17.00	6.25	6.38	−0.20
G#4	415.30	−16.00	7.32	7.16	0.20
A4	440.00	−15.00	8.40	8.04	0.40
Bb4	466.16	−14.00	9.20	9.03	0.20
B4	493.88	−13.00	10.01	10.00	0.00
C5[a]	523.25	−11.00	10.97	11.37	−0.30

[a] Note C5 was added only for the next experiment on relative and absolute pitch.

C.2 RESEARCH ETHICS AND SCRIPTS FOR PARTICIPANTS

As indicated in Section 5.3.2, the recruitment advertisement below was among the documents approved by the Research Ethics Committee of the University of Liverpool. Below are also the scripts to instruct participants in how to proceed during the pre- and post-training tests (i.e. baselines) and the training sessions.

12 December 2011 Version 1

Recruitment advert

Volunteers needed for research into feeling musical notes using vibration instead of sound

The Acoustics Research Unit at the University of Liverpool are seeking healthy adult volunteers for a new research project.

This experiment aims to identify the extent to which participants can correctly identify the relative pitch of two tones presented consecutively via vibration to the fingertip of the middle finger or the foot. The participant is played two tones each of 1s duration with a 1s gap between tones and then asked the question 'Is the second tone 'Higher' or 'Lower' than the first tone?'. A pre-training session (duration of 50 minutes with regular breaks) with a participant is used to establish a baseline against which the participant's improvement due to training can be assessed. This is followed by 16 training sessions (duration of 10 minutes) each on a different day, followed by a post-training session (duration of 50 minutes with regular breaks). In total, the time will be approximately 4.5 hours.

The tests will take place in the Acoustics Research Unit at the University of Liverpool.

Eligibility:
Age range: 18 to 70 years; Gender, Ethnicity and Race: All
Other: No impairment in the feeling or sensation in hands.

The research is funded by the Arts and Humanities Research Council (AHRC). This experiment is being carried out by the Acoustics Research Unit at the University of Liverpool in collaboration with the Royal Northern College of Music.

Contact details: Please contact Mr Saúl Maté-Cid (Postgraduate Research Assistant, Acoustics Research Unit) by email at **saulmate@liv.ac.uk**

University of Liverpool Ethics Reference No. *RETH000517*

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EXPERIMENT B1 <u>BASELINE</u> – SCRIPT FOR PARTICIPANT

As you read through the script below, please ask if you need any clarification.

ABOUT THE EXPERIMENT

- We are measuring the extent to which you can distinguish the *pitch* between two tones (representing different musical notes) produced by a vibrating finger pad. You will place the tip of the middle finger of your dominant hand (i.e. the hand that you normally write with) on the pad and you will be asked to say whether the second tone is higher or lower than the first tone.

- In this baseline session you will feel 420 pairs of tones. Each tone will last one second. They will be separated by a one-second pause. (Refer to diagram.)

- We are measuring the speed of your response as well as your accuracy, so you should respond as quickly as possible to the question "Is the second tone higher or lower than the first tone?" If you do not answer within three seconds you will feel the next pair of tones.

SCRIPT BEFORE <u>DEMO SESSION</u>

(The experimenter sits down to demonstrate equipment.)

- Please switch off your electronic mobile devices.

- Please remove any jewellery from the middle finger of your dominant hand and place it in the closable box provided for this purpose, which will be kept in front of you on the table during the session.

- You will place the tip of your middle finger *flat* on the metal disc. The middle part of the fingerprint should be gently placed in the middle of the disc. (Demonstrate.) Please try to avoid unnecessary movement of your body during the session.

- There will now be a short demonstration session. To start the session, you will press the space bar.

- You will see this question throughout the session at the top of the screen: Is the second tone higher or lower than the first tone?

- You will feel the two tones, separated by a one-second pause.

- Then please answer the question. Use the UP arrow key if you think the second tone was HIGHER. Use the DOWN arrow key if you think the second tone was LOWER. You have a maximum of three seconds to respond, <u>only while the response box on the screen is yellow</u>. (Refer to snapshots.)

- If you make a mistake you can change your response as long as you do it within three seconds, <u>while the response box is yellow.</u> Your valid response stays marked in red while the response box is yellow.

- When you have responded you will feel the next pair of tones.

- After three pairs of tones you will see the message "TAKE A BREAK". You will then be asked to respond to another three pairs of tones.

- Please keep your hand away from the keyboard whilst you feel the tones and be careful not to touch the buttons on the touchpad of the computer.

- Now please sit down and be careful with your feet and knees so that they do not knock the equipment.

- Remember to place the middle fingertip *flat* on the metal disc first and *only then* press the SPACE BAR and <u>this also applies when the message "TAKE A BREAK" appears</u>.

- For users of hearing aids, we would ideally like you to remove them. Whether you decide to remove the hearing aids or leave them in during the session, please make sure that there is consistency throughout the test (e.g. please don't remove the hearing aids once the session has started).

- To begin the demonstration session now, please put the headphones on (they play white noise continuously) and <u>place the fingertip *flat* on the metal disc and *only then* press the SPACE BAR.</u>

SCRIPT BEFORE <u>MAIN SESSION</u>

- After 20 minutes, halfway through the session, you will see the message "TAKE A BREAK". You may exit the room for up to 10 minutes before resuming the session.

- Every 5 minutes during the first half of the session, and every 4 minutes during the second half of the session, you will see the following message that gives you the option to rest your hands and stretch your fingers if you need to: "STRETCH YOUR FINGERS. WHEN YOU HAVE FINISHED PLACE YOUR HANDS AS THEY WERE BEFORE AND PRESS THE SPACE BAR TO CONTINUE". If you do not need the rest you can continue by pressing the SPACE BAR.

- For users of hearing aids, remember either to remove the hearing aids or to leave them in during the session.

- To begin the session now please put the headphones back on (if the white noise ceases please tell the experimenter). Remember to place the fingertip *flat* on the metal disc and *only then* press the SPACE BAR. (This also applies for messages offering a pause every 5 minutes.)

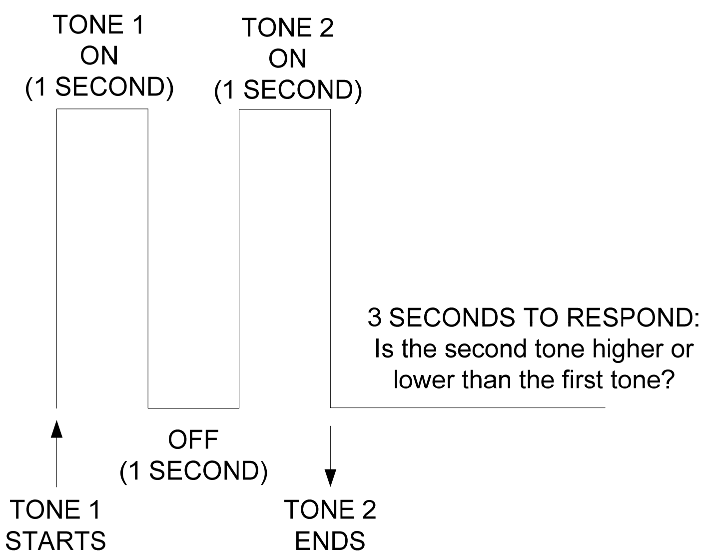
SCRIPT DURING MAIN SESSION BREAK

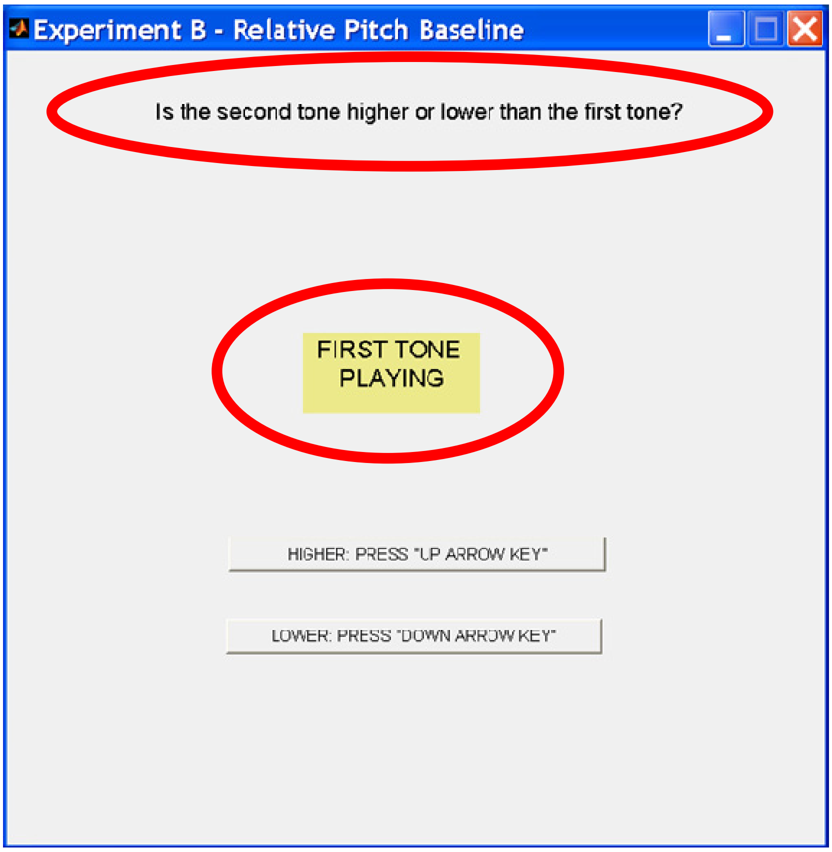
- At the end of the session you will see the message "SESSION FINISHED, THANK YOU".

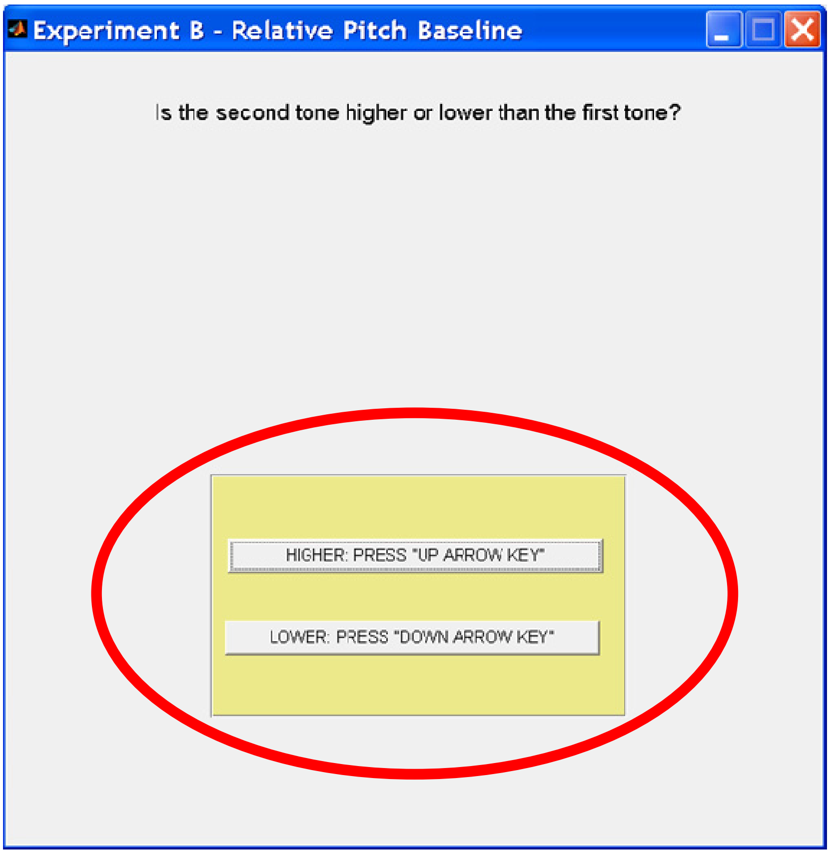
- Please do not press any more buttons and tell the experimenter that the session has finished.

- To resume the session now, please put the headphones back on and place the fingertip *flat* on the metal disc and *only then* press the SPACE BAR and continue until the end.

TONE PAIR: TWO DIFFERENT TONES ARE PLAYED




Experiment B - Relative Pitch Baseline
Is the second tone higher or lower than the first tone?
FIRST TONE PLAYING
HIGHER: PRESS "UP ARROW KEY"
LOWER: PRESS "DOWN ARROW KEY"


Experiment B - Relative Pitch Baseline
Is the second tone higher or lower than the first tone?
HIGHER: PRESS "UP ARROW KEY"
LOWER: PRESS "DOWN ARROW KEY"

***

EXPERIMENT B1 TRAINING – SCRIPT FOR PARTICIPANT

As you read through the instructions below, please ask if you need any clarification.

INITIAL SCRIPT (The experimenter sits down to demonstrate).

- Please switch off your electronic mobile devices.
- Please remove any jewellery from the middle finger of your dominant hand and place it in the closable box provided for this purpose, which will be kept in front of you on the table during the session.
- You will place the tip of your middle finger *flat* on the metal disc. The middle part of the fingerprint should be gently placed in the middle of the disc. (Demonstrate.) Please try to avoid unnecessary movement of your body during the session.

SCRIPT BEFORE DEMO SESSION
(Performed for the first training session only)

- There will now be a short demonstration session. To start the session, you will press the space bar.
- You will see this question throughout the session at the top of the screen: Is the second tone higher or lower than the first tone?
- You will feel the two tones, separated by a one-second pause. (Refer to diagram.)
- Then please answer the question. Use the UP arrow key if you think the second tone was HIGHER. Use the DOWN arrow key if you think the second tone was LOWER. You have a maximum of three seconds to respond while the response box is yellow. (Refer to snapshots.)
- If you make a mistake you can change your response as long as you do it within three seconds, while the response box is yellow. Your valid response stays marked in red while the response box is yellow.
- After three seconds you will get *feedback* as to whether your response was correct or incorrect. Then you have to press the SPACE BAR to continue.
- Please be careful not to touch the buttons on the touchpad of the computer.
- Now please sit down and be careful with your feet and knees so that they do not knock the equipment.

- For users of hearing aids, we would ideally like you to remove them. Whether you decide to remove the hearing aids or leave them in during the session, please make sure that there is consistency throughout the test (e.g. please don't remove the hearing aids once the session has started).

- To begin the demonstration session now, please put the headphones on (they play white noise continuously) and place the fingertip *flat* on the metal disc and *only then* press the SPACE BAR.

SCRIPT BEFORE MAIN SESSION

- Please note that each of the training sessions should last less than 10 minutes.

- At the end of the session you will see the message "SESSION FINISHED – PLEASE PRESS ENTER TO SEE YOUR RESULTS". Then please press ENTER to see your results and tell the experimenter that the session has finished.

- For users of hearing aids, remember either to remove the hearing aids or to leave them in during the session.

- To begin the session now please put the headphones on (if the white noise ceases please tell the experimenter). Remember to place the fingertip *flat* on the metal disc and *only then* press the SPACE BAR.

C.3 SUBJECTIVE MEASUREMENTS

Table C.2 shows the set of interval pairs ascending and descending in pitch that were used in the experiment, which is followed by an example of the raw data collected in a pre-training test. Section C.3.1 includes the training improvements for fingertips of participants with normal hearing that were non-significant. Section C.3.2 includes a comparison between both mean and median scores of participants with normal hearing in order to clarify how the discrimination of relative pitch with forefeet was more accurate compared with the results for the fingertips for intervals of one to six semitones in the post-training test.

Table C.2 Interval pairs ascending in pitch used in the experiment. (Interval pairs descending in pitch are shown in the next page.)

SEMITONES →		PAIR	1	PAIR	2	PAIR	3	PAIR	4	PAIR	5	PAIR	6	PAIR	7	PAIR	8	PAIR	9	PAIR	10	PAIR	11	PAIR	12
NOTE	PITCH																								OCTAVE
1	C3	1	1 2	47	1 3	91	1 4	133	1 5	173	1 6	211	1 7	247	1 8	281	1 9	313	1 10	343	1 11	371	1 12	397	1 13
2	C#3	2	2 3	48	2 4	92	2 5	134	2 6	174	2 7	212	2 8	248	2 9	282	2 10	314	2 11	344	2 12	372	2 13	398	2 14
3	D3	3	3 4	49	3 5	93	3 6	135	3 7	175	3 8	213	3 9	249	3 10	283	3 11	315	3 12	345	3 13	373	3 14	399	3 15
4	D#3	4	4 5	50	4 6	94	4 7	136	4 8	176	4 9	214	4 10	250	4 11	284	4 12	316	4 13	346	4 14	374	4 15	400	4 16
5	E3	5	5 6	51	5 7	95	5 8	137	5 9	177	5 10	215	5 11	251	5 12	285	5 13	317	5 14	347	5 15	375	5 16	401	5 17
6	F3	6	6 7	52	6 8	96	6 9	138	6 10	178	6 11	216	6 12	252	6 13	286	6 14	318	6 15	348	6 16	376	6 17	402	6 18
7	F#3	7	7 8	53	7 9	97	7 10	139	7 11	179	7 12	217	7 13	253	7 14	287	7 15	319	7 16	349	7 17	377	7 18	403	7 19
8	G3	8	8 9	54	8 10	98	8 11	140	8 12	180	8 13	218	8 14	254	8 15	288	8 16	320	8 17	350	8 18	378	8 19	404	8 20
9	G#3	9	9 10	55	9 11	99	9 12	141	9 13	181	9 14	219	9 15	255	9 16	289	9 17	321	9 18	351	9 19	379	9 20	405	9 21
10	A3	10	10 11	56	10 12	100	10 13	142	10 14	182	10 15	220	10 16	256	10 17	290	10 18	322	10 19	352	10 20	380	10 21	406	10 22
11	Bb3	11	11 12	57	11 13	101	11 14	143	11 15	183	11 16	221	11 17	257	11 18	291	11 19	323	11 20	353	11 21	381	11 22	407	11 23
12	B3	12	12 13	58	12 14	102	12 15	144	12 16	184	12 17	222	12 18	258	12 19	292	12 20	324	12 21	354	12 22	382	12 23	408	12 24
13	C4	13	13 14	59	13 15	103	13 16	145	13 17	185	13 18	223	13 19	259	13 20	293	13 21	325	13 22	355	13 23	383	13 24		
14	C#4	14	14 15	60	14 16	104	14 17	146	14 18	186	14 19	224	14 20	260	14 21	294	14 22	326	14 23	356	14 24				
15	D4	15	15 16	61	15 17	105	15 18	147	15 19	187	15 20	225	15 21	261	15 22	295	15 23	327	15 24						
16	D#4	16	16 17	62	16 18	106	16 19	148	16 20	188	16 21	226	16 22	262	16 23	296	16 24								
17	E4	17	17 18	63	17 19	107	17 20	149	17 21	189	17 22	227	17 23	263	17 24										
18	F4	18	18 19	64	18 20	108	18 21	150	18 22	190	18 23	228	18 24												
19	F#4	19	19 20	65	19 21	109	19 22	151	19 23	191	19 24														
20	G4	20	20 21	66	20 22	110	20 23	152	20 24																
21	G#4	21	21 22	67	21 23	111	21 24																		
22	A4	22	22 23	68	22 24																				
23	Bb4	23	23 24																						
24	B4																								

Table C.2 (continued) Interval pairs descending in pitch used in the experiment.

SEMITONES → NOTE	PITCH	PAIR	1		PAIR	2		PAIR	3		PAIR	4		PAIR	5		PAIR	6		PAIR	7		PAIR	8		PAIR	9		PAIR	10		PAIR	11		PAIR	12 OCTAVE	
1	C3	24	24	23	69	24	22	112	24	21	153	24	20	192	24	19	229	24	18	264	24	17	297	24	16	328	24	15	357	24	14	384	24	13	409	24	12
2	C#3	25	23	22	70	23	21	113	23	20	154	23	19	193	23	18	230	23	17	265	23	16	298	23	15	329	23	14	358	23	13	385	23	12	410	23	11
3	D3	26	22	21	71	22	20	114	22	19	155	22	18	194	22	17	231	22	16	266	22	15	299	22	14	330	22	13	359	22	12	386	22	11	411	22	10
4	D#3	27	21	20	72	21	19	115	21	18	156	21	17	195	21	16	232	21	15	267	21	14	300	21	13	331	21	12	360	21	11	387	21	10	412	21	9
5	E3	28	20	19	73	20	18	116	20	17	157	20	16	196	20	15	233	20	14	268	20	13	301	20	12	332	20	11	361	20	10	388	20	9	413	20	8
6	F3	29	19	18	74	19	17	117	19	16	158	19	15	197	19	14	234	19	13	269	19	12	302	19	11	333	19	10	362	19	9	389	19	8	414	19	7
7	F#3	30	18	17	75	18	16	118	18	15	159	18	14	198	18	13	235	18	12	270	18	11	303	18	10	334	18	9	363	18	8	390	18	7	415	18	6
8	G3	31	17	16	76	17	15	119	17	14	160	17	13	199	17	12	236	17	11	271	17	10	304	17	9	335	17	8	364	17	7	391	17	6	416	17	5
9	G#3	32	16	15	77	16	14	120	16	13	161	16	12	200	16	11	237	16	10	272	16	9	305	16	8	336	16	7	365	16	6	392	16	5	417	16	4
10	A3	33	15	14	78	15	13	121	15	12	162	15	11	201	15	10	238	15	9	273	15	8	306	15	7	337	15	6	366	15	5	393	15	4	418	15	3
11	Bb3	34	14	13	79	14	12	122	14	11	163	14	10	202	14	9	239	14	8	274	14	7	307	14	6	338	14	5	367	14	4	394	14	3	419	14	2
12	B3	35	13	12	80	13	11	123	13	10	164	13	9	203	13	8	240	13	7	275	13	6	308	13	5	339	13	4	368	13	3	395	13	2	420	13	1
13	C4	36	12	11	81	12	10	124	12	9	165	12	8	204	12	7	241	12	6	276	12	5	309	12	4	340	12	3	369	12	2	396	12	1			
14	C#4	37	11	10	82	11	9	125	11	8	166	11	7	205	11	6	242	11	5	277	11	4	310	11	3	341	11	2	370	11	1						
15	D4	38	10	9	83	10	8	126	10	7	167	10	6	206	10	5	243	10	4	278	10	3	311	10	2	342	10	1									
16	D#4	39	9	8	84	9	7	127	9	6	168	9	5	207	9	4	244	9	3	279	9	2	312	9	1												
17	E4	40	8	7	85	8	6	128	8	5	169	8	4	208	8	3	245	8	2	280	8	1															
18	F4	41	7	6	86	7	5	129	7	4	170	7	3	209	7	2	246	7	1																		
19	F#4	42	6	5	87	6	4	130	6	3	171	6	2	210	6	1																					
20	G4	43	5	4	88	5	3	131	5	2	172	5	1																								
21	G#4	44	4	3	89	4	2	132	4	1																											
22	A4	45	3	2	90	3	1																														
23	Bb4	46	2	1																																	
24	B4																																				

Below is an example of raw data collected in a pre-training test (i.e. baseline).

```
*** *** *** *** *** *** *** *** *** *** ***
RELATIVE PITCH BASELINE opened: 15-Feb-2012 10:04:25
Participant's name: [snip]
START: 15-Feb-2012 10:06:08
Is the second tone higher or lower than the first tone?
------- ------   ---------  -----------  ------------   ------------
                             PARTICIPANT
                             ANSWER:       RESULTS:        REACTION TIME
                             1 = Higher    1 = Correct     (seconds):
                            -1 = Lower    -1 = Incorrect  -1 = Anticipated
 ORDER   PAIR #   PAIR NAME  0 = Missing   0 = Missing     0 = Missing
------- ------   ---------  -----------  ------------   ------------
      1     189    17  22        1             1              0.57
      2      32    16  15       -1             1              1.49
      3      28    20  19        1            -1              0.22
      4     352    10  20        1             1              0.52
      5     326    14  23        1             1              0.23
    ...     ...   ... ...      ...           ...              ...
    198      39     9   8       -1             1              0.45
    199      43     5   4       -1             1              0.35
    200      89     4   2       -1             1              0.27

PAUSE: 15-Feb-2012 10:28:06
Correct answers in part 1: 160
Incorrect answers in part 1: 38
Missing answers in part 1: 2
CONTINUE: 15-Feb-2012 10:34:16

    201     194    22  17       -1             1              0.24
    202     218     8  14        1             1              0.24
    ...     ...   ... ...      ...           ...              ...
    418      96     6   9        1             1              0.32
    419     333    19  10       -1             1              0.18
    420     294    14  22        1             1              0.29

SESSION FINISHED, 420 pairs of tones played: 15-Feb-2012 10:58:03
---------------------------
Correct answers in part 2: 181
Incorrect answers in part 2: 38
Missing answers in part 2: 1

***************************
Correct answers in TOTAL: 341 (81%)
Incorrect answers in TOTAL: 76 (18%)
Missing answers in TOTAL: 3 (1%)
***************************
```

C.3.1 Fingertips

As indicated in Section 5.4.1.2, improvements from fingertips of participants with normal hearing that were statistically non-significant are shown in Figure C.1.

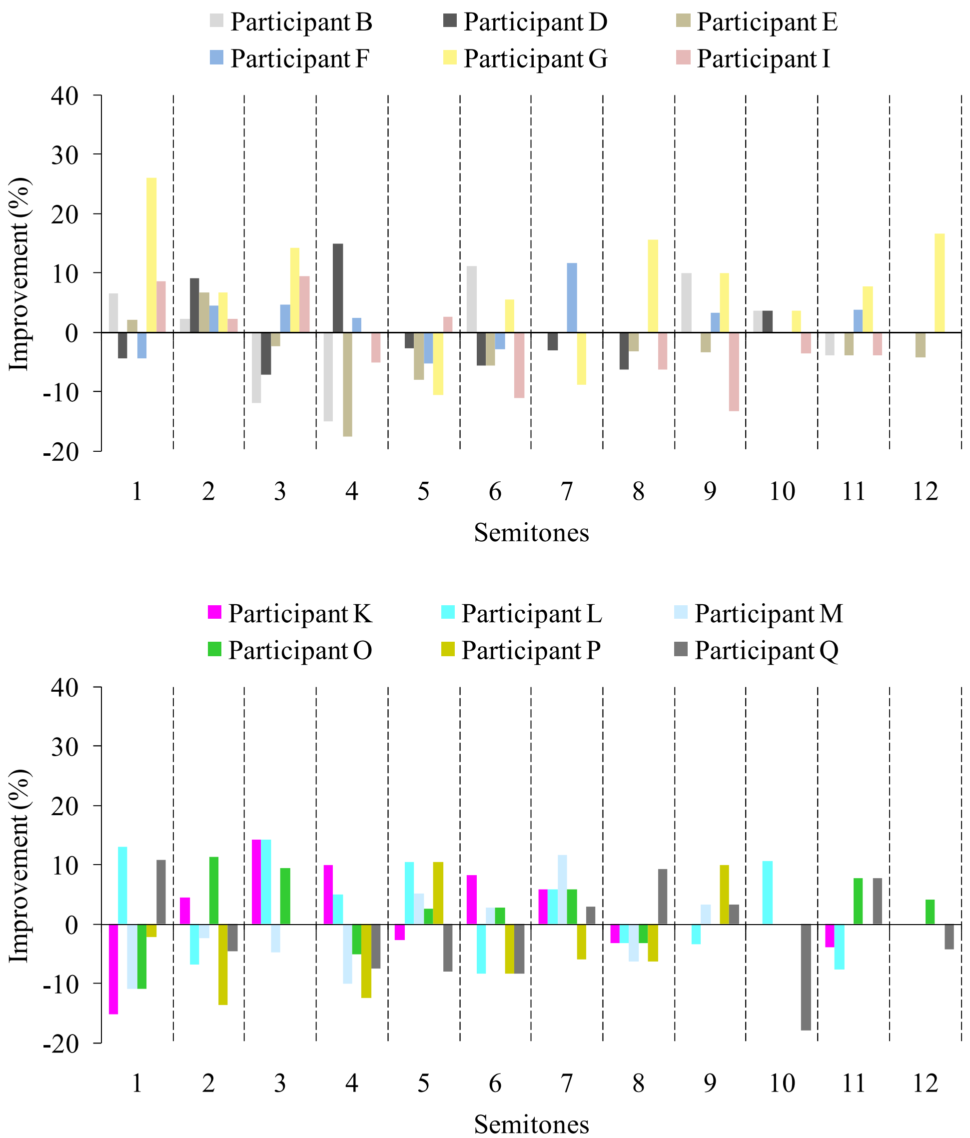


Figure C.1 Top and bottom: non-significant improvement in relative pitch discrimination between pre- and post-training tests for fingertips of each participant and for each interval in semitones.

C.3.2 Forefeet

The results in Section 5.4.2 (cf. Figures 5.19 and 5.20) suggested that training provided a particular benefit for the discrimination of small-sized intervals. Table C.3 shows that relatively large scores obtained with forefeet happened more frequently for intervals of one to six semitones in the post-training session when using both median values and mean values. The results using medians were found to be consistent with those using means in order to clarify how the results of forefeet were more accurate compared with the results of fingertips for intervals of one to six semitones in the post-training test.

Table C.3 Comparison of medians used in Figures 5.19 and 5.20 and means used in Figure 5.18. Changes ≥ +5% are printed in bold type to indicate marked improvements.

Semitones	Fingertips			Forefeet		
	Pre-training	Post-training	Change	Pre-training	Post-training	Change
			Medians			
1	52.17	60.87	**8.70**	50.00	63.04	**13.04**
2	61.36	65.91	4.55	63.64	65.91	2.27
3	66.67	71.43	4.76	64.29	71.43	**7.14**
4	77.50	72.50	−5.00	70.00	75.00	**5.00**
5	76.32	81.58	**5.26**	71.05	81.58	**10.53**
6	83.33	83.33	0.00	66.67	80.56	**13.89**
7	82.35	88.24	**5.88**	82.35	82.35	0.00
8	93.75	93.75	0.00	84.38	87.50	3.13
9	93.33	96.67	3.33	86.67	86.67	0.00
10	92.86	96.43	3.57	82.14	92.86	**10.72**
11	96.15	96.15	0.00	84.62	88.46	3.84
12	100.00	100.00	0.00	87.50	95.83	**8.33**
			Means			
1	55.12	58.57	3.45	54.11	64.49	**10.38**
2	61.76	64.84	3.07	60.86	66.67	**5.81**
3	64.99	69.47	4.48	61.64	70.90	**9.26**
4	72.79	75.88	3.09	67.78	75.00	**7.22**
5	76.47	81.73	**5.26**	68.42	77.78	**9.36**
6	81.54	84.64	3.10	70.37	83.02	**12.65**
7	82.70	88.41	**5.71**	78.1	82.35	4.25
8	88.42	92.46	4.04	81.25	84.72	3.47
9	86.27	94.71	**8.43**	85.19	84.44	-0.75
10	88.66	94.54	**5.88**	84.13	90.48	**6.35**
11	88.69	95.48	**6.79**	83.76	89.32	**5.56**
12	92.16	98.28	**6.13**	87.96	92.59	4.63

APPENDIX D: RELATIVE & ABSOLUTE PITCH LEARNING

This appendix for Chapter 6 includes Section D.1 to show the script for participants and Section D.2 to complement the description of subjective measurements, which includes an example for the raw data collected during an experimental session.

D.1 SCRIPT FOR PARTICIPANTS

As indicated in Section 6.3.2, below is the script to instruct participants in how to proceed during the experimental sessions using feet. Participants were briefed before starting the first session only.

EXPERIMENT B2 (FEET) – PREPARATION FOR PARTICIPANT

ABOUT THE EXPERIMENT

1. This experiment aims to identify the extent to which participants can learn and identify the pitches of musical notes presented via vibration to the foot.

2. You will place the toes and the ball of your right foot on a vibrating disc and you will be asked to choose or identify the notes that are played. You will then select your answer using the electronic piano keyboard provided.

3. There will be nine sessions in total and each session will take place on a different day. Each session will have three parts: Study Period, Test 1 and Test 2.

   In the **Study Period** you will use the piano keyboard to familiarise yourself with the vibrations produced by each of the keys.

   Test 1 and Test 2 will consist of a series of "trials". In each trial you will feel the vibrations caused by the playing of a pair of notes. Each note will last one second and the two notes will be separated by a one-second pause. (Refer to diagram and piano pictures.)

   In **Test 1**, the first of the two notes will always be Middle C, followed by any other note. In **Test 2**, the same note will be played twice and this could be any of the highlighted notes on the screen provided.

4. We are also measuring the speed of your response as well as your accuracy, so you should respond using the piano keyboard as quickly as possible to the questions displayed on screen. You will have a maximum of three seconds to respond.

INSTRUCTIONS FOR DEMO SESSION
(Experimenter sits down to demonstrate equipment)

5. Please switch off your electronic mobile devices and enter the test chamber in order to watch the demo on how to sit and how to place the feet correctly on the foot rig.

6. Please stay beside the experimenter outside of the white-surfaced areas to watch the demo. *(The experimenter demonstrates, reads the instructions aloud and provides any clarification needed. The experimenter wears clean socks to demonstrate without touching the foot disc.)*

7. There will now be a short demonstration session. To start the session, you will move the laptop *gently* towards you, wear headphones, and enter your name and your current session number on the computer screen. Then you will continue to the study period.

8. It is important that you read and follow carefully the instructions on the screen.

9. Please note that this piano keyboard is of a special type and its keys may be very sensitive. Please press the keys one at a time and firmly but gently.

STUDY PERIOD

10. You will see this message throughout the session at the top of the screen: "Place your foot ready to feel the notes". Please place the toes and the ball of your right foot *flat* on the disc.

11. Then please press the space bar to start the Study Period. This is divided into two parts: The first lasts 30 seconds to study the Middle C only and the second lasts 1 minute 30 seconds (1.5 minutes) to study all the highlighted notes. After you have pressed the space bar you will be able to play Middle C as often as you like. If you press a different key you will be reminded to play Middle C only until the 30 seconds have run out.

12. When the 30 seconds have run out, you will see the message "30 seconds up, now press the space bar to start 1.5 minutes". After you have pressed the space bar you will be able to play all the highlighted keys on the piano. If you press a different key you will be reminded to play the highlighted notes only and you will be able to continue doing so until the 1.5 minutes have run out.

13. The Study Period ends when the 1.5 minutes have run out. Then you will be asked to continue to Test 1.

TEST 1 AND TEST 2

14. You will see the message throughout the session at the top of the screen: "Place your foot ready to feel the notes".

15. Then please press the space bar to start playing the notes. In Test 1, the reference note, Middle C, will be followed by a test note. In Test 2, a test note will be played twice. You will feel the two notes, separated by a one-second pause. (Refer to diagram again.)

16. Then please answer the question "which note was it?" by choosing your answer on the piano keyboard. You have a maximum of three seconds to respond. Please choose your answer on the piano keyboard only while the response box on the screen is yellow. (Refer to snapshots.)

17. If you make a mistake you can change your response as long as you do it within three seconds, while the response box is yellow. Your response stays marked in blue, unless you press other keys that are not used in the experiment at all. (Refer to piano pictures again.)

18. After three seconds you will get *feedback* as to whether your response was correct or incorrect. After you see the feedback, please press the space bar to continue as indicated on the screen.

19. At the end of Test 1, you will be asked to continue to Test 2. (*At the end of Test 2, the experimenter closes the demo and opens it again ready for the participant to begin the demo.*)

****

20. Please sit down on the secondary chair to remove the footwear and roll your trousers or dress above your right knee if possible. All the equipment, foot discs and surfaces have been cleaned before your arrival. Please walk only barefoot on the white surfaces.

21. Before sitting down on the pedestal chair, please note that if you want to adjust the height of the pedestal chair your foot may not be placed on the foot discs. This is to avoid damaging the equipment which is very sensitive. If you want to adjust the height on the pedestal chair you have to place your feet first on the pedestal.

22. Now, as demonstrated before, please sit down comfortably (and adjust height) in the pedestal chair and maintain an upright posture.

23. Please place the heel, the ball of the foot and the toes *gently* on the foot discs. (*Refer to above demo*)

24. Move the laptop *gently* towards you *(Refer to above demo.)*

25. Please try to avoid unnecessary movement of your body during the test.

26. To begin the demo session now, please enter and save your name and session number: 1. Please put the headphones on (they play white noise continuously) and continue to the study period and until the demo session is finished.

27. *(After the demo session, the participant is asked to move aside the laptop and to vacate the chair. If needed, further clarification is provided or the demonstration is repeated.)*

INSTRUCTIONS FOR MAIN SESSION

28. *(The experimenter closes the demo version, opens the final long version, moves aside the laptop and vacates the chair for the participant.)*

29. Please sit down on the foot rig and move the laptop *gently* towards you as before.

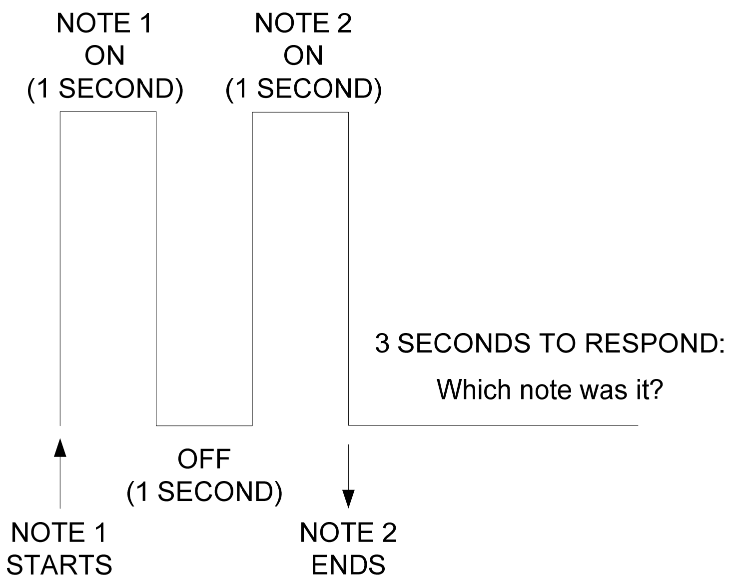
30. To call for assistance, please press the provided hand button continuously or just walk out of the room. Please note that the experimenter will be outside by the room for about the first five minutes only.

31. Please ensure that you place your foot *gently* and correctly on the discs to start the test.

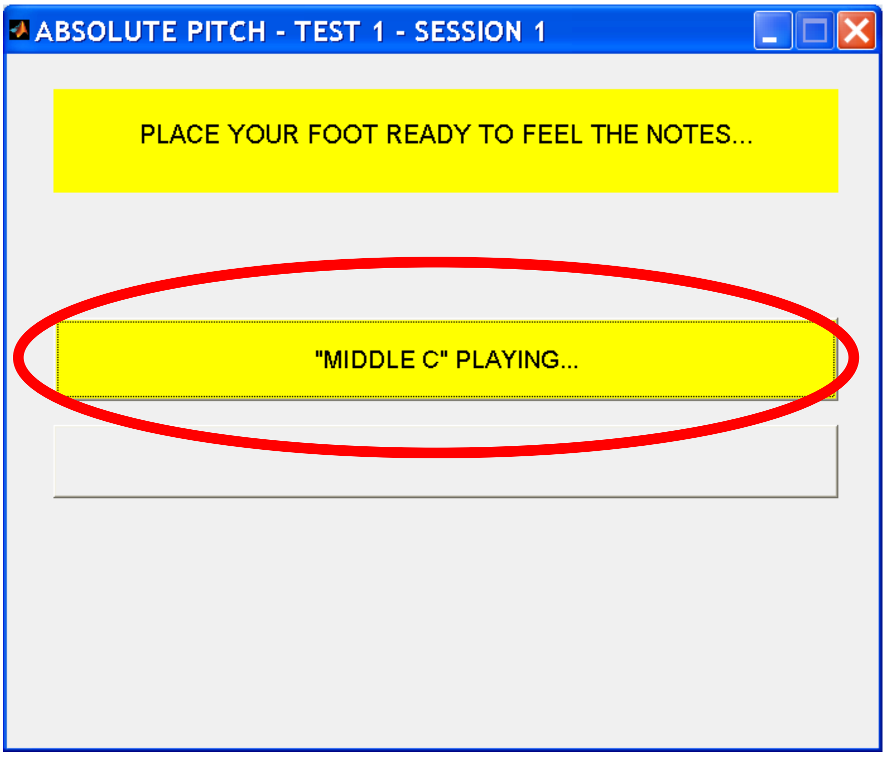
32. To begin the main session now, please enter and save your name and session number: 1. Please put the headphones back on (if the white noise ceases please tell the experimenter) and continue to the study period and until the main session is finished.

33. At the end of Test 2, please walk out of the room and tell the experimenter the session has finished.

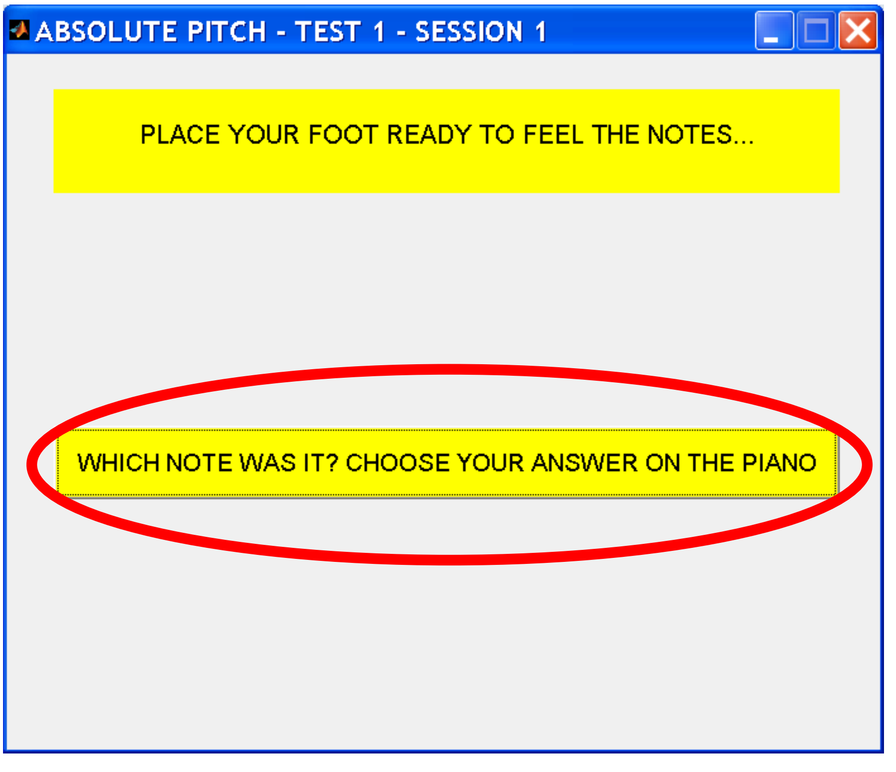
NOTE PAIR: TWO NOTES ARE PLAYED



<u>TEST 1</u>:	NOTE 1 IS THE REFERENCE NOTE MIDDLE C. NOTE 2 IS A TEST NOTE.
<u>TEST 2</u>:	NOTE 1 IS A TEST NOTE. NOTE 2 = NOTE 1



NOTES ARE BEING PLAYED. THE RESPONSE BOX IS NOT YET YELLOW.



NOTES STOPPED.

THE RESPONSE BOX IS NOW YELLOW WAITING FOR THE ANSWER.

D.2 Subjective measurements

As indicated in Section 6.3.2, below is an example for the GUI data output.

```
*** *** *** *** *** *** *** *** *** *** ***
ABSOLUTE PITCH TRAINING, SESSION No.: 1

PARTICIPANT'S NAME: ...

 NOTE    KEY
   1      C3
   2      D3
   3      E3
   4      G3
   5      A3
   6      C4
   7      D4
   8      E4
   9      G4
  10      A4
  11      C5

============
START TEST 1 - PLAYING NOTES: 18-Feb-2013 12:49:03
-----   -------------   -------- ---------------  ------------  -------------  --------------
                                  PAIR             PARTICIPANT
                                  ORIENTATION:     ANSWER/NOTE:  RESULT:        REACTION TIME
                                  1 = Ascending    1-11 = C3-C5  1 = Correct    (seconds):
                                 -1 = Descending  -1 = Other    -1 = Incorrect -1 = Anticipated
 ORDER   PAIR NAME      INTERVAL  0 = Unison       0 = Missing   0 = Missing    0 = Missing
-----   -------------   -------- ---------------  ------------  -------------  --------------
   1       6    11 z1      12          1               11            1              1.51
   2       6    1  z1      12         -1                1            1              1.13
   3       6    11 x1      12          1               11            1              1.39
   4       6    6  y1       0          0                1           -1              0.99
   5       6    6  x1       0          0                1           -1               1
   6       6    6  z1       0          0                1           -1              1.14
   7       6    1  x1      12         -1                6           -1              0.82
   8       6    11 y1      12          1               11            1              0.73
   9       6    1  y1      12         -1                1            1              1.58
-------------------
Correct answers in TEST 1:    5 (56%)

Incorrect answers in TEST 1:  4 (44%)

Missing answers in TEST 1:    0 (0%)
---------------------------

TEST 1 FINISHED: 18-Feb-2013 12:50:20

Elapsed time since START TEST 1 is 76.4787 seconds (i.e. 1.2747 minutes).

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START TEST 2 - PLAYING NOTES: 18-Feb-2013 12:50:29
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                                  PAIR             PARTICIPANT
                                  ORIENTATION:     ANSWER/NOTE:  RESULT:        REACTION TIME
                                  1 = Ascending    1-11 = C3-C5  1 = Correct    (seconds):
                                 -1 = Descending  -1 = Other    -1 = Incorrect -1 = Anticipated
 ORDER   PAIR NAME      INTERVAL  0 = Unison       0 = Missing   0 = Missing    0 = Missing
-----   -------------   -------- ---------------  ------------  -------------  --------------
   1      11    11 x1       0          0               11            1              0.85
   2       1    1  z1       0          0                1            1              0.75
   3       1    1  x1       0          0                1            1              0.95
   4       6    6  y1       0          0                6            1              0.97
   5      11    11 z1       0          0               11            1              1.09
   6       6    6  x1       0          0                1           -1              1.11
   7      11    11 y1       0          0               11            1              1.1
   8       6    6  z1       0          0                6            1              1.08
   9       1    1  y1       0          0                6           -1              2.29
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Correct answers in TEST 2:    7 (78%)

Incorrect answers in TEST 2:  2 (22%)

Missing answers in TEST 2:    0 (0%)
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TEST 2 FINISHED: 18-Feb-2013 12:51:46

Elapsed time since START TEST 2 is 77.5739 seconds (i.e. 1.2929 minutes).
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As indicated in Section 6.4.1.3, below is the procedure to calculate the mean change in the percentage of correct responses in terms of the proximity of new tones to active tones for each session in the identification tests. The procedure was the same using the results obtained from the fingertip or the forefoot. Table D.1 shows the total percentage of correct responses via the fingertip including all participants in tests 1 and 2 using the active notes in each session (cf. highlighted keys in Figure 6.1).

Table D.1 Total percentage of scores for correct responses for all participants.

Session	C3	D3	E3	G3	A3	C4	D4	E4	G4	A4	C5
1	97.22					93.52					97.22
2	74.07			58.33		69.44					94.44
3	73.15			71.30		65.74			60.19		50.93
4	54.63		40.74	47.22		56.48			59.26		52.78
5	62.96		47.22	49.07		48.15		35.19	53.70		43.52
6	57.41		43.52	51.85		50.93		35.19	40.74	30.56	31.48
7	63.89		46.30	30.56	31.48	43.52		40.74	32.41	24.07	29.63
8	39.81	20.37	31.48	26.85	26.85	44.44		42.59	37.96	25.00	31.48
9	43.52	18.52	25.93	33.33	25.93	34.26	17.59	27.78	35.19	25.93	33.33

Table D.2 includes the difference in the scores for correct responses between adjacent sessions.

Table D.2 Decrease in the participants' responses from one session to the next.

Session	C3	D3	E3	G3	A3	C4	D4	E4	G4	A4	C5
1	C3					C4					C5
2	−23.15			G3		−24.07					−2.78
3	−0.93			12.96		−3.70			G4		−43.52
4	−18.52		E3	−24.07		−9.26			−0.93		1.85
5	8.33		6.48	1.85		−8.33		E4	−5.56		−9.26
6	−5.56		−3.70	2.78		2.78		0.00	−12.96	A4	−12.04
7	6.48		2.78	−21.30	A3	−7.41		5.56	−8.33	−6.48	−1.85
8	−24.07	D3	−14.81	−3.70	−4.63	0.93		1.85	5.56	0.93	1.85
9	3.70	−1.85	−5.56	6.48	−0.93	−10.19	D4	−14.81	−2.78	0.93	1.85

Table D.3 includes the resulting interval distance when new keys were introduced in a session. The interval distance is shown below as the number of semitones between the active keys and a newly introduced key in each session.

Table D.3 Distance in semitones that new tones are separated from active tones.

Session	C3	D3	E3	G3	A3	C4	D4	E4	G4	A4	C5
1	C3					C4					C5
2	7			G3		5					17
3	19			12		7			G4		5
4	4		E3	3		8			15		20
5	16		12	9		4		E4	3		8
6	21		17	14		9		5	2	A4	3
7	9		5	2	A3	3		7	10	12	15
8	2	D3	2	5	7	10		14	17	19	22
9	14	12	10	7	5	2	D4	2	5	7	10

Table D.4 shows the resulting percentage from dividing the change in the response from one session to the next shown in Table D.2 by the number of semitones that a new tone in a session was separated from an active tone (see Table D.3).

Table D.4 The response change between adjacent sessions is shown relative to the distance in semitones that new tones are separated from active tones in each session.

Session	C3	D3	E3	G3	A3	C4	D4	E4	G4	A4	C5
1	C3					C4					C5
2	−3.31			G3		−4.81					−0.16
3	−0.05			1.08		−0.53			G4		−8.70
4	−4.63		E3	−8.02		−1.16			−0.06		0.09
5	0.52		0.54	0.21		−2.08		E4	−1.85		−1.16
6	−0.26		−0.22	0.20		0.31		0.00	−6.48	A4	−4.01
7	0.72		0.56	−10.65	A3	−2.47		0.79	−0.83	−0.54	−0.12
8	−12.04	D3	−7.41	−0.74	−0.66	0.09		0.13	0.33	0.05	0.08
9	0.26	−0.15	−0.56	0.93	−0.19	−5.09	D4	−7.41	−0.56	0.13	0.19

Table D.5 shows the results from Table D.4 re-arranged by interval (cf. Table D.3). The outcome is the mean percentage of the participants' response change, which is shown in Figure 6.4 of Section 6.4.1.3.

Table D.5 Percentage of the response change rearranged by interval size in semitones.

Semitones								Total	Count	Mean
2	−12.04	−7.41	−10.65	−5.09	−7.41	−6.48		−49.07	6	−8.18
3	−8.02	−2.47	−1.85	−4.01				−16.36	4	−4.09
4	−4.63	−2.08						−6.71	2	−3.36
5	0.56	−0.74	−0.19	−4.81	0.00	−0.56	−8.70	−14.44	7	−2.06
7	−3.31	0.93	−0.66	−0.53	0.79	0.13		−2.65	6	−0.44
8	−1.16	−1.16						−2.31	2	−1.16
9	0.72	0.21	0.31					1.23	3	0.41
10	−0.56	0.09	−0.83	0.19				−1.11	4	−0.28
12	−0.15	0.54	−0.54	1.08				0.93	4	0.23
14	0.26	0.20	0.13					0.60	3	0.20
15	−0.06	−0.12						−0.19	2	−0.09
16	0.52							0.52	1	0.52
17	−0.22	−0.16	0.33					−0.05	3	−0.02
19	−0.05	0.05						0.00	2	0.00
20	0.09							0.09	1	0.09
21	−0.26							−0.26	1	−0.26
22	0.08							0.08	1	0.08