Pitch perception in musical chords for cochlear implant users

Susanna Griffin

UCL Ear Institute

Faculty of Brain Sciences

A thesis submitted for the degree of

Doctor of Philosophy

September 2016

Declaration

I, Susanna Griffin, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Susanna Griffin

Abstract

Many people with severe or profound hearing loss are able to benefit from electronic hearing provided by a cochlear implant (CI); however, perception of music is often reported to be unsatisfactory. Due to the sound processing restrictions and current spread, CI users do not always perceive accurate pitch information, which adversely affects their ability to perceive and enjoy music. This thesis examines the factors affecting pitch perception in musical contexts for CI recipients.

A questionnaire study was carried out in order to pilot and validate a questionnaire about music listening experience and enjoyment for bot pre- and post-lingually deafened CI users. Results of this study were generally more positive that previous questionnaire studies, especially from pre-lingually deafened CI users, but the majority of respondents were keen for an improvement to their music listening experience.

CI users took part in a pilot study of the Chord Discrimination Test, identifying the “odd one out” of three different chord stimuli in which the difference was one semitone. The individual notes of the chords were presented either simultaneously or sequentially and spanned one to three octaves. Results showed significantly higher discrimination scores for simultaneously presented chords, possibly due to auditory memory difficulties for the sequential task.

In the main study phase, participants undertook the tests with stimuli comprising both pure tones and simulated piano tones, and chord differences ranging from one to three semitones. No significant difference between the two tone conditions was found, but performance was significantly better when the difference between the chords was three semitones. A change in the top note of the chord was easier to detect than a change in the middle note. Peak performance occurred in the C5 octave range, which also correlated with scores on a consonant recognition test, suggesting a relationship between speech and music perception in this frequency area.

Children took part in an abridged version of the Chord Discrimination Test. Children with normal hearing were able to identify a one semitone difference between musical chords, while hearing impaired children performaed at chance. Some children were also able to accurately identify a half semitone difference. NH children's results showed an effect whereby performance fell when the notes of the chord remained within the C major scale, suggesting a potential for the Chord Discrimination Test to be used in assessments of sensitivity to musical scales.

The Chord Discrimination Test was shown to be a versatile and adaptable tool with many potential applications for use in settings such as musical training, and pitch perception assessments in both research and clinical settings.

Acknowledgements

I would like to thank my supervisors Debi Vickers and Andy Faulkner for their many hours of guidance, advice and support over the past five years. I would also like to thank Advanced Bionics for the funding that allowed this project to be carried out.

I am very grateful to the cochlear implant users who took the time to take part in my study and provide useful feedback at all stages of the study. Thanks go as well to the staff of Laycock Primary School who were so helpful in facilitating the testing that went on there, and to the Year 1 and Year 2 students who so cheerfully and enthusiastically took part.

Finally I owe a huge debt of gratitude to my parents David and Karen Griffin for their unending support!

Contents

List of figures

List of tables

Chapter 1 - Introduction

1.1 Music and electrical hearing

Music is a central component of many people's lives. While music may often be classed along with other forms of entertainment such as film, sport or television, many people feel a strong emotional or spiritual connection to music which goes far beyond its simple entertainment value. In the words of Victor Hugo, the author of 'Les Miserables':

> "Music expresses that which cannot be put into words and that which cannot remain silent".

As well as enhancing the enjoyment of mundane daily tasks, music is also a vital component of many of the crucial milestones of human life, such as weddings and funerals. Music transcends cultural boundaries, brings people together, and can have therapeutic benefits. Music is such an integral part of society that it is often almost impossible to avoid listening to music, whether in shops, restaurants, lifts or waiting areas. Because of this, an unsatisfactory music listening experience not only deprives an individual of the enjoyment that music can bring, but can make situations where music is unavoidable difficult to tolerate. Therefore an inadequate perception of music, as for example experienced by those with sensorineural hearing loss, can hamper an individual's enjoyment of life. For such individuals, hearing can be restored either by a hearing aid (HA) or cochlear implant (CI). These devices can, however, pose their own problems when it comes to the appreciation of music. In this thesis the primary focus in on perception of music for people with CIs.

CIs deliver hearing by electrically stimulating the auditory nerves in response to sound. The history of electrical hearing stretches back to 1790, when Alessandro Volta sought to discover what would happen when he placed conductive rods, which were connected by wires to either end of a 50V battery, into his ears. The result was a series of booms and bubbling noises, which were sufficiently disturbing for Volta to abandon this experiment (Wilson & Dorman, 2008). It was more than 150 years later that the first operation to implant a device to stimulate the auditory nerve occurred in 1957. Further development of this technology commenced in the early 1960s, and from the late 1970s people with little or no hearing have been able to take advantage of electronic hearing by the use of a CI.

The first CI patients were implanted with single channel devices which provided little more than an awareness of environmental sounds. In 1977, 13 such patients existed in the United States. A study of the auditory abilities of these patients concluded:

> "Although the subjects could not understand speech through their prostheses, they did score significantly higher on tests of lipreading and recognition of environmental sounds with their prostheses activated than without them" (Bilger et al., 1977).

Even up to the 1980s, many experts in the field believed that this was the most that could be hoped for (Wilson & Dorman, 2008). However, in the intervening years, there have been major strides forward in CI technology, including the introduction of multichannel devices and advances in sound processing strategies. Currently, more than 324,000 people worldwide hear with the aid of a CI (NIH Publication No. 11-4798). Speech recognition and perception of environmental sounds is for many users exceptional, particularly in quiet, with many recipients achieving scores over 90% in standard tests (Gifford et al., 2008). However, due to limitations in pitch perception provided by the implant, music perception and enjoyment remains challenging for many CI users.

CI manufacturers devise different strategies in an attempt to address the problems with delivery of pitch information. These include strategies designed to increase the number of perceptual channels of information in so-called ‘virtual channel’ strategies such that the fine frequency detail would lead to improvements in pitch perception. Others attempt to improve transmission of fine structure information which should convey the temporal pitch information. With advances in CI technology, expectations of outcomes with the devices have increased. Many CI users cite improvement in music perception as their most important hope for future CI technologies (Mirza et al., 2003; McDermott, 2004).

The primary aim of the research reported in this thesis was to examine pitch perception of CI users in a musical context. Musical chords were chosen as the component of music with which to examine CI users’ pitch perception due their prevalence in Western music and their adaptability to a number of different parameters. A further aim was to discover which of these parameters of stimuli will provide the most useful information regarding CI users' pitch perception in music. Additionally, this research aimed to examine the current level of music enjoyment experienced by CI users, and whether this is related to their pitch perception abilities. This introductory chapter details the importance and prominence of chords in Western music, gives a background to the perception of pitch in normal hearing, and examines the ways in which CI processing strategies can affect pitch and music perception.

1.2 Musical chords: Theory, history and psychology

1.2.1 Music theory

The term 'chord' can in practice be defined as 'three or more notes sounded together' (Taylor, 2000; Parncutt, 2012). In this research only the simplest three-note chords were used. The chord discrimination test described in this thesis was developed as an expansion of a chord test described by Vongpaisal et al. (2006), which tested listeners' abilities to discriminate between two successive chords presented in an arpeggiated form. The chords used in this study were major, minor and augmented, which will be described in more detail in this section.

Western music divides the range of audible sounds into a range of fixed notes. These notes are best pictured as the keys on a piano keyboard, although in practice, the human voice and many musical instruments (such as the violin or trombone) are able to produce an infinite number of pitches, regardless of whether they fall exactly on a pitch denoted by a piano key. Within the structure of fixed notes as denoted on a keyboard, musical notes are divided into octaves. Two notes are said to be an octave apart if the fundamental frequency of the lower note is exactly half of the higher note. These two notes are said to be of the same “pitch class” and will then be given then same letter name, from A to G, known in music psychology as the chroma (Schnupp et al., 2011; Parncutt, 2012). A number denotes their position on the keyboard (for example, C4 is 262 Hz, C5 is 523 Hz, C6 is 1047 Hz, and so on). Figure 1.1 shows a complete piano keyboard with all notes and frequencies labelled according to this system.

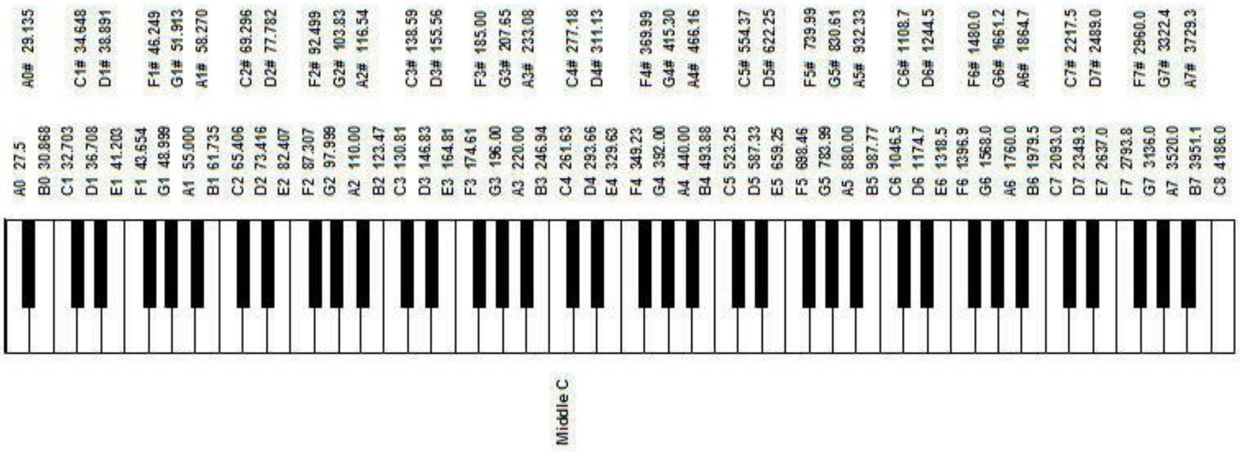


Figure 1.1: A full 88 key piano keyboard, with all notes labelled by chroma (A to G), position on the scale (0 to 8) and frequency. From: Science Buddies Staff (2015).

The octave is divided into twelve semitones. On a keyboard, adjacent notes (whether white to white or white to black) are a semitone apart. The ratio between the frequencies of two notes a semitone apart is the 12th root of 2, approximately 1:1.06 (Deutsch, 1999). Normal hearing (NH) listeners, particularly those who are musically trained, have been shown to be able to discriminate frequency differences far smaller than a semitone (Dallos, 1996). However, some non-musical and untrained NH listeners can do very poorly in pitch discrimination tasks and cannot discriminate a difference of a semitone (Micheyl et al., 2006)

While an octave contains a sequence of twelve semitones, in the majority of music (particularly that composed prior to the 20th century) only a selection of notes from these twelve will typically be used (Taylor, 2000). When arranged in ascending or descending order, this selection is known as a scale. The simplest scales is that of C major, which on a piano keyboard consists of white notes only. Within a scale, notes are often categorised in terms of their distance from the lowest note of the scale (i.e. the chroma) as intervals. The thirteen possible intervals are illustrated in figure 1.2. Musical chords are made up of combinations of two or more of these intervals.

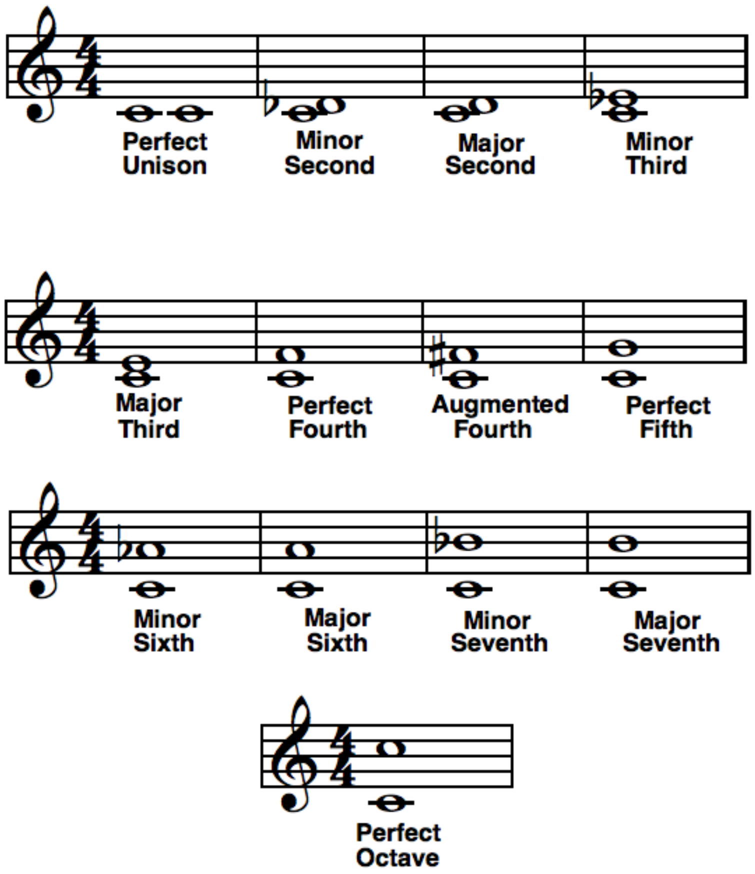


Figure 1.2: The thirteen possible musical intervals from a root note of C. From Rader (2010).

One focus of the research detailed in this thesis was the development of a musical chord discrimination task which was based upon three specific kinds of chords: major, minor and augmented triads. A triad is a chord which consists of a root note plus the third note and fifth note above the root (Taylor, 2000). A series of notes is said to be a major triad if it comprises the 1st, 5th and 8th semitone of a scale. In terms of intervals relative to the root note, a major triad contains a major third and a perfect fifth. Therefore, this triad contains two unequal intervals of four (C to E) and three (E to G) semitones respectively. For example, a C major triad will comprise C, E and G. Figure 1.3 shows twelve notes on a piano keyboard between two successive C notes, with the notes which comprise the C major tonic triad highlighted in grey.

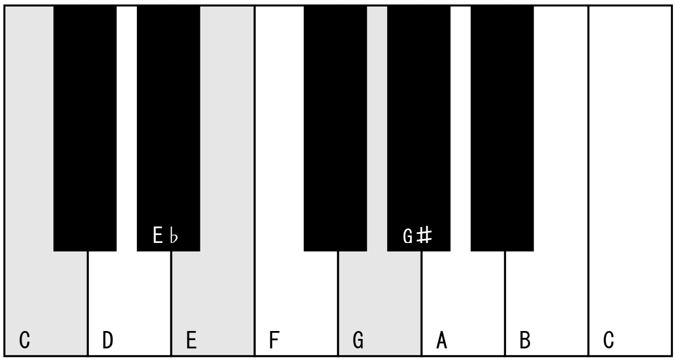


Figure 1.3: The notes of a C major triad, as played on a keyboard instrum**ent.**

A minor triad contains the 1st, 4th and 8th semitone (e.g. C, E♭ and G), which is a minor third and a perfect fifth relative to the chord root. This means it also contains two unequal intervals, of three (C to E♭) and four (E♭ to G) semitones. Figure 1.4 shows twelve notes on a piano keyboard, with the notes which comprise the C minor tonic triad highlighted in grey.

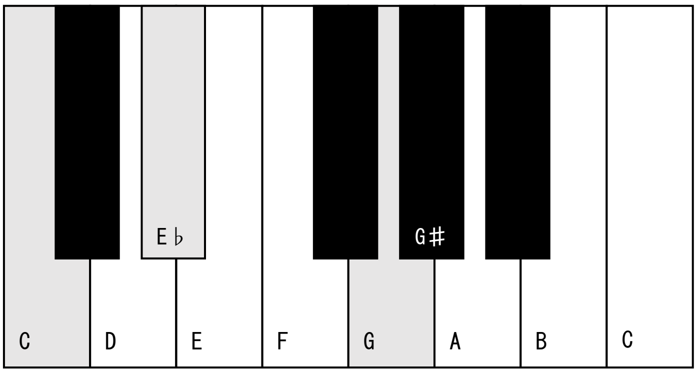


Figure 1.4: The notes of a C minor triad, as played on a keyboard instrument.

An augmented triad contains the 1st, 5th and 9th semitone (e.g. C, E and G♯) which is a major third and an augmented fifth, which gives it two equal intervals of four semitones each (C to E and E to G♯). Figure 1.5 shows twelve notes on a piano keyboard, with the notes which comprise the C augmented tonic triad highlighted with in grey.

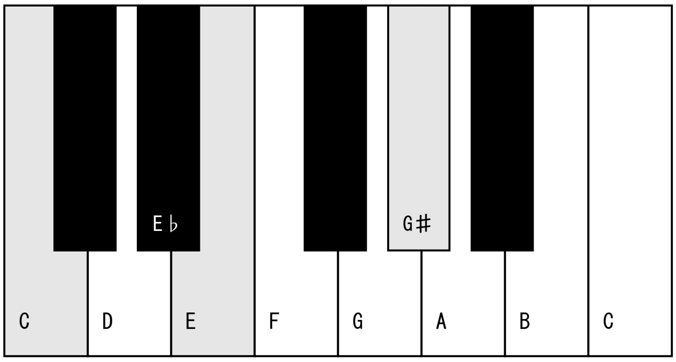


Figure 1.5: The notes of a C augmented triad, as played on a keyboard instrument.

Within a given musical scale, there exists a hierarchy of tones (Krumhansl & Cuddy, 2010). Certain tones within the scale are more emphasized, repeated more often, appear more stable, and occur at structurally significant points in the musical piece. These tones are higher in the hierarchy than others in the scale. In Western music, the hierarchy occurs as follows in table 1.1:

Table 1.1: Hierarchy of tones according to Krumhansl & Cuddy (2010)

Position in hierarchy	Note	Example: C major scale
TOP	First tone of the scale (tonic)	C
↓	Fifth tone of the scale (dominant)	G
↓	Third tone of the scale (mediant)	E
↓	All other tones in the scale	D, F, A, B
BOTTOM	All non-scale tones	C♯, D♯, F♯, G♯, A♯

The three tones considered highest in the hierarchy are the three tones that make up the tonic major triad. When changing a major chord to a minor, the third tone of the scale (third in the hierarchy) is dropped down a semitone to a note at the bottom of the hierarchy. Changing a major to an augmented involves a change of the fifth tone of the scale (second in the hierarchy) which raises a semitone again to a note at the bottom of the hierarchy. When examining major, minor and augmented chords in terms of hierarchy, therefore, it is worth noting that the change from major to augmented removes the note of the chord (the dominant) which is second only in the hierarchy to the chord root (the tonic). In a change from a major chord to a minor chord, both the tonic and dominant remain intact.

1.2.2 Chords in music history

Chords are a common element of Western classical music, which has a rich and complex history stretching back nearly one thousand years. Polyphony – the concept of sounding two or more contrasting voices together – was a key component of church music in the 13th century, with one or more additional voices accompanying chant hymn (Grout et al., 2010). Compositions in which two or more voices sang different notes according to particular rules were known as organa (singular: organum). Organa typically featured parallel fifths and octaves, which were generally avoided in later composition periods such as the Baroque and classical eras (Parncutt, 2012). This style of music, with the emphasis on interwoven melody lines with notes played in succession, is sometimes referred to as a horizontal approach (Busch, 1986; Parncutt, 2012). In the Baroque era (1600 – 1750), composers utilised a form of notation known as basso continuo, in which the melody and bass line were specified by the composer but performers filled in the appropriate chords (Grout et al., 2010). This approach, in which chords are played in sequence, with all notes of the chord sounded simultaneously, can be referred to as a vertical approach (Busch, 1986; Parncutt, 2012). The emphasis on harmony – the simultaneous sounding of different notes – is a distinguishing feature of Western music, to the extent that it has been argued that it has led to less intricate rhythmic or melodic structures than are found in other musical traditions (Taylor, 2000; Huron, 1994). In the late 17th and early 18th century, compositions began to appear which featured arpeggios, in which the notes of the chord were played one after the other in sequence. This has the effect of eliciting the impression of the chord without the notes being played simultaneously. An example of this approach was the Alberti bass which was widely used during the Classical music period (1730 – 1832) (Grout et al., 2010). The two presentations of chords, simultaneous (or harmonic) and sequential (or arpeggiated), are at the centre of the research detailed in this thesis.

1.2.3 Perception of musical chords

Chords are an integral part of Western music. They are one of the few musical constructions that retain their integrity outside of the context of a larger musical composition (Fishman et al., 2001). For all listeners, regardless of musical background, some chords are perceived as having greater qualities of stability or consonance than others. Of the three main chords used in the research described in this thesis, the major chord is perceived as the most consonant, followed by the minor, and the augmented is least consonant (Roberts, 1986). The degree to which a chord is judged as consonant tends to be related to the availability of its component notes within the diatonic scale, which is a scale comprising two steps of a semitone interspersed between five steps of a tone (two semitones). The diatonic major scale, along with the harmonic minor, is the foundation of the vast majority of Western music (Huron, 1994). Unlike major and minor chords, the notes of an augmented triad cannot be derived from a diatonic scale. Adults have been shown to process diatonic melodies more easily than nondiatonic melodies (Deutsch, 1982, 1986).

Trainor and Trehub (1993) carried out an experiment to examine the ability of adults and infants to detect a semitone change in a five-note melody. The standard in each trial was either a major triad or an augmented triad, with the notes presented sequentially. Both adults and infants were significantly better at identifying the semitone change from a major chord standard than from an augmented chord standard. This suggests that a preference for the major chord is an innate aspect of auditory processing.

Huron (1991) described the phenomenon of tonal fusion, in which multiple simultaneous tones are perceived as components of a single complex tone. The interval for which tonal fusion is most likely to occur is the unison, followed by the octave, with the perfect fifth the third most likely interval for tonal fusion. Major and minor chords both include an interval of a perfect fifth. Because of tonal fusion, it may be difficult for listeners to distinguish the numbers of tones contained within a chord. Above three notes, even trained musicians have difficulty reporting the number of notes in a chord, although musicians are significantly more accurate at denumerating concurrent voices than non-musicians (Huron, 1989; Ockelford, 2012). However, there are certain individuals with advanced skills in this task. Research with blind and autistic participants has shown that some such individuals have the capacity not only to tell the number of notes within a chord but also to report the exact notes making up the chord's composition, a phenomenon termed 'chordal disaggregation' (Ockelford, 2012; Mazzeschi, 2015). This ability is more common in individuals with absolute pitch, which is the ability to identify the pitch of a heard note without reference to any other pitch.

Major chords are described as sounding happy, and minor chords sad. There is evidence to suggest that while these emotional associations are in some part attributable to learning, they are not arbitrary, and may be linked to vocal prosody associated with the different emotional states (Peretz et al., 1998; Bowling, 2013). The emotional content of a major or minor chord is processed by the brain as rapidly as the emotional content of a facial expression, suggesting these chords have very deeply ingrained emotional connotations for listeners (Bakker & Martin, 2014).

1.2.4 Summary

Chords have been an integral part of Western music, in both their simultaneous and sequential presentations, for several hundred years. Perception of chords is reliant upon an accurate perception of the pitches of the notes contained within them. The following section gives an introduction to the perception of pitch in a normally-hearing auditory system.

1.3 Pitch

Pitch can be defined as the property of a sound which can be used to order notes from low to high. The American Standards Association (1960) defined pitch as ‘That attribute of auditory sensation in terms of which sound may be ordered on a musical scale’. It is the perceptual correlate of the frequency of a pure tone, or the fundamental frequency of a complex sound.

The ability to discern differences in pitch is vital for the perception and recognition of two fundamental components of Western music: melody (changes in the pitch and duration of notes over time) and harmony (combinations of simultaneous sounds which differ in pitch). Accurate perception of small changes in pitch is much more important for the perception of music than it is for the perception of speech (with the possible exception of tonal languages such as Mandarin, which use changes in intonation to indicate lexical differences). Meaningful changes in music occur with a difference of just one semitone, which represents a pitch change of approximately 6%. This can be heard for example in the distinction between a major and a minor chord, or a major and an augmented chord. Thus, to be able to fully experience music, a listener requires a fine resolution in pitch perception which may not be available to CI users (McDermott, 2004).

There are two main theories of pitch perception in normal hearing, which highlight either the importance of place cues or temporal information in the perception of pitch. While the theories place emphasis on different mechanisms for the perception of pitch information, both place and temporal cues are considered important in modern theories of pitch perception.

1.3.1 Pitch perception: Place theory

Place theories of pitch perception relate to the tonotopic organisation of the basilar membrane (BM), which runs along the length of the cochlea and separates the scala media and the scala tympani. Distributed along the BM are up to 20,000 hair cells. Each of these hair cells respond to pressure variations caused by sound waves and stimulate the auditory nerve. At each point along the BM, there is a characteristic frequency which is partially determined by the mechanical properties of the BM (width, thickness and stiffness) changing along its length. The membrane is thinner and stiffer at the base of the cochlea, and wider and less stiff at the apex. The natural resonance of each section is distinct, and different sites produce maximum displacement in response to different frequencies. The frequency that leads to maximal displacement is known as the characteristic frequency for its respective region. A representation of characteristic frequencies at various points along the BM can be seen in Figure 1.6.

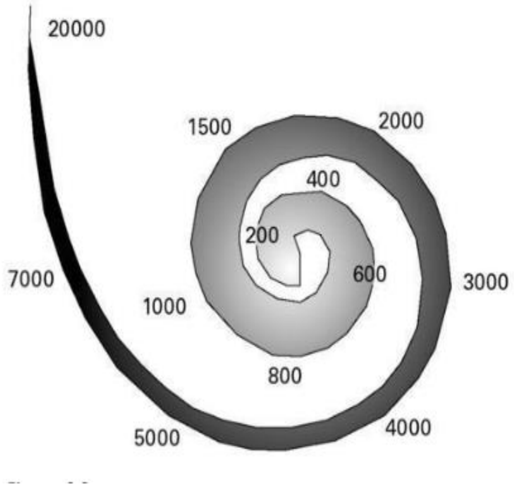


Figure 1.6: The tonotopic organisation of the basilar membrane. with high frequency waves creating maximum vibration at the base and low frequency waves at the apex. From Schnupp et al. (2011).

Sounds at high frequencies produce maximum displacement to areas of the basilar membrane at the base of the cochlea. Low frequency sounds produce vibrations along the BM with a maximum at or near the apex. This tonotopy is preserved in the vestibulocochlear nerve, which in turn triggers neurons with appropriate characteristic frequencies (Moore, 1997). It should be noted that the place code of the basilar membrane relates to the frequency content of a stimulus (that is, the rate of periodic vibration of the sound wave of a pure tone), and not necessarily its pitch (the perception of the sound’s position on a musical scale) (Schnupp et al., 2011).

1.3.2 Pitch perception: Temporal theory

Temporal theory refers to the periodicity of a sound, and the timing of the neural firings it evokes. When neural firing occurs, an electrical current known as the action potential passes down the axon of the neuron and causes chemicals (neurotransmitters) to be released into the synaptic gap between the axon terminal and the target neuron. The dendrites or cell body of the neuron targeted by the neurotransmitter contain receptors with which the neurotransmitter binds (Ward, 2006). In an undamaged auditory system, electrical signals derived from sound vibrations are transmitted via the auditory nerve to the auditory brainstem and auditory cortex. Temporal theory of pitch perception depends upon phase locking, in which each firing occurs at approximately the same phase of the stimulating waveform, although not necessarily on every cycle (Moore, 1997). Figure 1.7 illustrates an example of phase locking. These firings usually correspond to maximum amplitude of the motion of the BM (Schnupp et al., 2011).

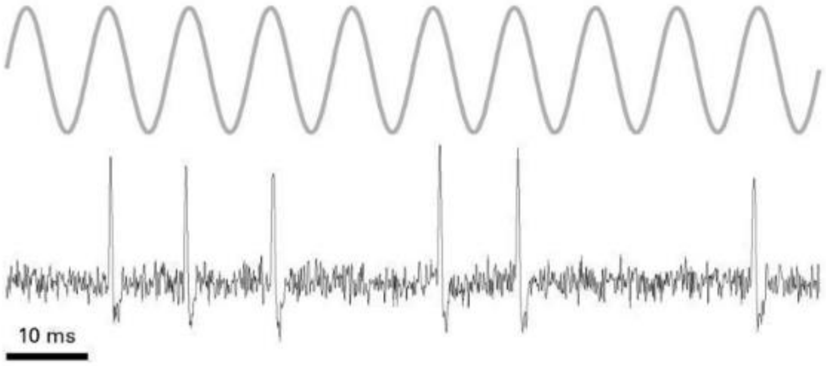


Figure 1.7: A simulation of phase locking in an auditory nerve fibre recording. The upper half of the diagram shows a periodic waveform. The lower half shows the nerve firing on some of the cycles of the waveform, at the same phase each time. From Schnupp, Nelken & King (2011).

1.3.3 Perception of pitch in pure and complex tones

Pure tones are tones created by a single periodic sine wave. These tones are almost always computer generated and rarely occur in nature. One way to measure the perception of pure tones is to measure the smallest detectable difference between two frequencies, or frequency difference limens (FDL). An early review of FDL experiments (Wier et al.,1977) found that the FDL of pure tones tends to increase as frequency increases. Additionally, FDLs are very small compared to musically significant differences. For example, at 1 kHz at 60 to 70 dBSPL, a 2 to 3 Hz difference can be detected. To put this in a musical context, the nearest musical notes to the 1 kHz frequency are B5 (988 Hz) and C6 (1047 Hz) – thus the semitone difference represents a change of 59 Hz, which is much greater than the reported FDL.

Above 5 kHz, perception of melody becomes very difficult. In one experiment looking at the effect of frequency on pitch perception, listeners were presented with two tones, and asked to modify the second to be an octave above the first. For tones below 5 kHz, participants were fairly accurate at placing the second tone at double the frequency of the first. However, once the second tone rose above 5 kHz, the ability to do this became erratic (Ward, 1954). Other studies have also shown a lack of a clear sense of melody above 5 kHz (Attneave & Olson, 1971; Ohgushi & Hatoh 1991).

Complex tones are comprised of a number of different frequency components in combination, as illustrated in figure 1.8. Complex tones account for the vast majority of sounds heard on a daily basis. It is difficult to account for the perceptual findings regarding complex tones based on place theory alone, due to the fact that complex tones are made up of a number of harmonics which have frequencies at multiples of the fundamental frequency (F0). For example, a complex tone with an F0 of 200 Hz will have harmonics at multiples of 200Hz. Harmonics at lower frequencies are resolved by the peripheral auditory system, but harmonics at higher frequencies are not (Moore, 1997).

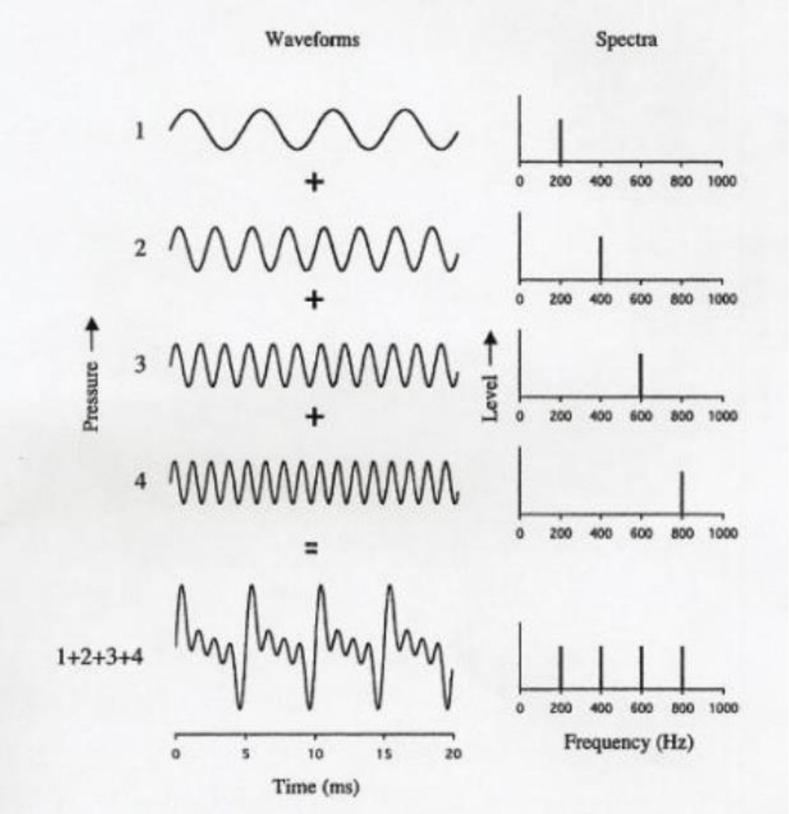


Figure 1.8: An example of a complex tone made up of a number of pure tones. The different component waveforms are shown in number 1 to 4, with the complex tone formed from them shown at the bottom of the diagram. Spectra of the components and the full complex tones are shown on the right. From Plack et al. (2006)

It was initially believed that the frequency of a complex tone would be equivalent to its F0. However, the pitch of a tone can be perceived even if the fundamental frequency component is not present, which is a phenomenon known as “the missing fundamental”. Removing the F0 does not alter the pitch of the tone, merely its timbre (Moore, 1997). It has been shown that the lower harmonics above the fundamental are the most important for providing the pitch of a tone (Rasch & Plomp, 1982). The pitch will also remain the same if the lowest harmonic is masked by noise (Licklider 1956).

There are a number of different theories put forward to account for the perception of complex tones. These are broadly divided onto two groups: pattern recognition models, and temporal models (Moore, 1997). Wightman (1973) suggested a pattern recognition model inspired by visual pattern recognition theories, which account for, as an example, the human ability to recognise a particular letter of the alphabet despite considerable differences in typeface or handwriting. This model comprises three stages. The first stage involves a coarse spectral analysis of the input stimulus. The second is extraction of the pitches of the individual components of the complex tone via a Fourier transformation. The third stage uses the output of this transformation to extract the pitch of the input stimulus. By contrast, temporal models address the different functions of lower resolved harmonics and higher unresolved harmonics. Pitch can be extracted either from phase locking to individual low resolved harmonics, or to the envelope of unresolved higher harmonics (Cheveigne, 2005). In an experiment using synthesised stimuli which has the envelope of one sound and the fine structure of another, Smith et al. (2002) found that fine structure information was more important for pitch perception than envelope information.

1.3.4 Pitch perception: summary

The preceding section described the nature of pitch perception as it occurs in a normally hearing ear. However, for a hearing impaired (HI) listener listening through a CI, there are different considerations. The following section provides an introduction to CIs and highlights some of the differences between normal hearing and hearing through a CI.

1.4 Introduction to cochlear implants

The CI is a neural prosthesis which bypasses the damaged or missing hair cells along the length of the cochlea and stimulates the auditory nerve via electrical currents. These currents are delivered by an array of electrode contacts positioned within the cochlea. The CI is made up of both external and internal components. The external components comprise two elements: a microphone and a sound processor. The microphone picks up environmental sounds, and the sound processor transforms these sounds into a set of stimuli which are to be transferred to the internal components via a transcutaneous link. In modern CIs, this microphone and processor package is worn behind the ear. Internal CI components include a receiver-stimulator and an electrode array. The implanted receiver-stimulator decodes the received information and generates stimuli which are transmitted to the electrode array inside the cochlea. The electrodes deliver current which directly stimulates the auditory nerve and creates the sensation of sound.

There are three main CI manufacturers whose devices appear in the research described in this thesis. These are MED-EL, based in Innsbruck, Austria; Cochlear, based in Sydney, Australia; and Advanced Bionics (AB), based in California, USA. The following sections will go into more detail about the different devices and strategies used by these three companies.

The approach for delivery of electrical stimulation can vary across devices from different manufacturers, but typically biphasic pulses are used as a carrier for the signal. The delivery of pulses can vary in rate, pulsewidth, and number of available channels. A variety of different sound processing strategies, each with their own unique approach, transform the microphone input into electrical pulses conveying sound information (Wilson, 2006). There are a number of parameters common to all CIs which affect the sound processing strategies. All these elements can be altered, and are often different across the CI companies. Some of these key elements are described below.

1.4.1 Transcutaneous transmission

The sound processor, in combination with a microphone and battery pack, is worn behind the ear. A thin cable connects this to the external transmitting coil containing a magnet, and is held in place by attraction to a further magnet within the implanted receiver-stimulator under the skin (Wilson & Dorman 2008b, see figure 1.9). In this way the input sounds are transmitted via a transcutaneous link to the implanted electrodes.

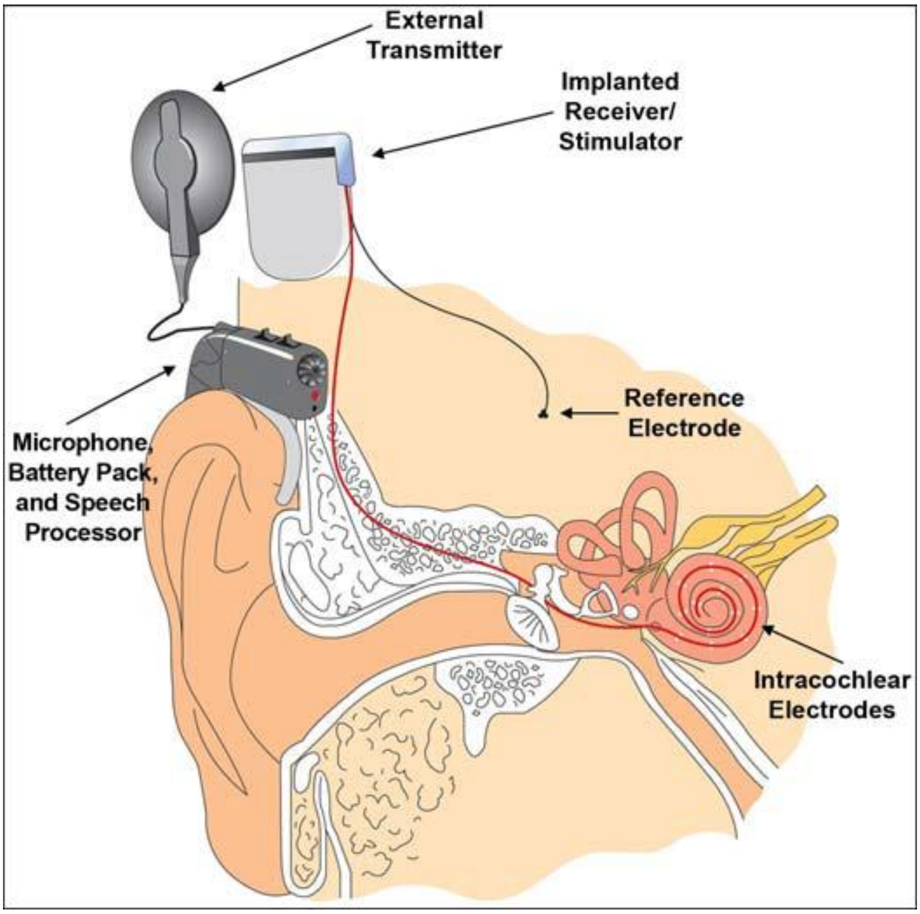


Figure 1.9: Diagram of the external and internal components of the cochlear implant. From Wilson & Dorman, 2008b.

1.4.2 Internal receiver package

The internal receiver-stimulator is a hermetically sealed package which sits in a flattened or recessed portion of skull, posterior to the pinna. Signals received by the package are decoded, rectified and integrated to send stimuli to and provide power for the implanted electrode array (Wilson, 2006). As well as the internal receiver-stimulator, a reference electrode is implanted at some distance from the cochlea, which regulates current intensity, impedance and power (Ramos-Miguel et al,, 2015). The usual position is within the temporalis muscle, but for some devices, a metallic band situated outside of the receiver-stimulator package functions as the reference electrode (Wilson & Dorman, 2008b).

1.4.3 Front end processing

The initial processing stages of the sound processing strategies may include: pre-amplification to increase the level of weak signals; pre-emphasis for increasing the gain for high frequency sounds; automatic gain control, which keeps the output sound at a constant level regardless of variations in the input sound, and helps to reduce distortion; noise cancellation; and sensitivity control, which controls the input from the microphone to adjust to the minimum amplitude of the input sound required for stimulation (Arora, 2012). A flow chart of the separate stages of front end processing can be seen in figure 1.10.

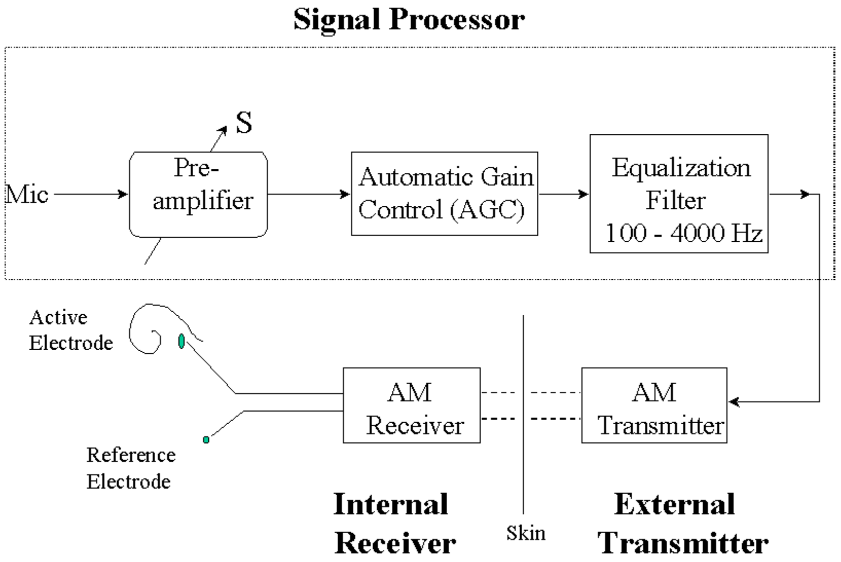


Figure 1.10. Flowchart showing the different stages of front-end processing in a cochlear implant sound processor. From Loizou (1999).

1.4.4 Filter banks

Most sound processing strategies utilise a series of filter banks to process the acoustic signal. Input sounds are separated into different frequency components via a bank of bandpass filters. Each filter allows a certain range of frequencies to pass through to the next stage of processing, which typically involves envelope detection, compression and modulation (Wilson & Dorman, 2008). A greater number of frequency bands may allow for a more accurate representation of the pitch of the input stimulus, as a greater amount of tonotopy can therefore be preserved. Different processing strategies use different numbers of filter banks, typically between 12 and 22, with current strategies using one analysis filter per electrode (Looi, 2008).

1.4.5 Electrode array

All CIs contain an array of between 12 and 22 electrodes, which are intended to be inserted into the scala tympani. The placement of the array can vary in terms of its depth of insertion, optimally between 25mm and 31mm or 1.5 turns of the cochlea. There can also be variations between implants in the distance of the electrode array from the modiolus - the central axis around which the turns of the cochlea are seen, consisting of conically formed spongy bone (Zeng et al., 2008).

A deeper insertion may provide an improved match of the cochlear implant pitch delivery to the characteristic frequency. It provides access to more apical regions of the cochlea, and given the tonotopic organisation of the BM, provides a more complete match between the input frequency and the frequency of delivery.

However, over-insertion can cause damage to the cochlea. A shallower insertion may have the advantage of being more likely to preserve some residual hearing but there is a greater offset between tonotopic representation and the characteristic frequencies of the placement region, and thus pitch perception is potentially compromised. The overall efficiency of information transfer between the electrode and the auditory nerve is another important factor with respect to outcomes for the implant (Zeng et al., 2008).

Pitch ranking abilities have been compared in NH participants, CI users with long electrode arrays (22mm), and short array (10mm) CI users with electro-acoustic stimulation (EAS) (Gfeller et al., 2007). Results showed a significantly poorer performance from the long electrode group when compared to both the NH and short electrode CI users. The short electrode group, who were able to take advantage of both acoustic stimulation in the apex of the cochlea and electric stimulation in the basal end, performed similarly to NH listeners at lower frequencies but performance dropped in the higher frequency range, suggesting low-frequency information was being provided by amplification of residual hearing.

1.4.6 Stimulation rate and configuration

In most current day sound processing strategies, electrodes within the cochlea are stimulated in a monopolar coupling configuration (Srinivasan et al., 2013). This is a system whereby an extracochlear electrode is used as a return (reference) electrode for the stimulation of each intracochlear electrode. However, this causes large current spread across the cochlea, which can have the effect of stimulating a larger population of neurons than is ideal, and adjacent electrodes may stimulate the same groups of neurons (Townshend et al., 1987). This can have a negative effect on pitch perception. More focussed stimulation can be achieved using a bipolar configuration, where a nearby intracochlear electrode is used as a reference, and tripolar stimulation uses two intracochlear electrodes (Wilson, 2004; Srinivasan et al., 2013). Schematics of all three configurations can be seen in figure 1.11. One problem with the more focussed stimulation configurations is that they tend to be power hungry options and the trade-off between power consumption and focussing needs to be considered.

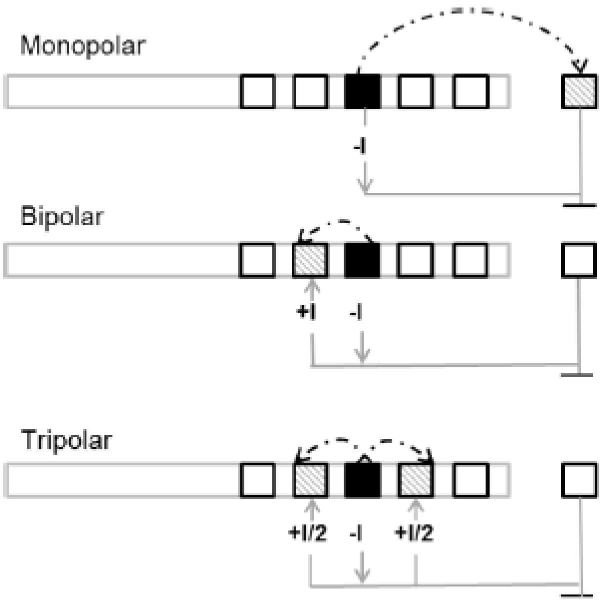


Figure 1.11: Current flow in monopolar, bipolar and tripolar configurations. From Zhu et al., 2012.

Rate of stimulation may vary from less than 500 pulses per second (pps) per channel, to over 5000 pps per channel (Fu & Shannon, 2000; Arora, 2012). Studies looking at the optimal rate of stimulation for speech perception have shown a great deal of variability in results, with little evidence for improvements in higher rates of stimulation and indeed some CI users showing decreased speech perception at higher rates (Vandali et al., 2000).

1.4.7 Current sources

CIs may contain a single current source or multiple current sources. Those with a single source generate the current according to available amplitude information, and a switching network connects the single source to multiple electrodes one-by-one. Devices such as AB's HiRes 90K and MED-EL's Sonata have multiple current sources and thus do not require a switching network. The sources are used simultaneously or sequentially to generate positive and negative phases of stimulation (Zeng et al., 2008). This allows simultaneous stimulation of more than one electrode, which has the potential to increase the number of pitch percepts by controlling the delivery of current to adjacent fixed electrodes such that the channel interaction creates intermediate pitch percepts (see section 1.5.8 on virtual channels).

1.5 Sound processing strategies

1.5.1 Early strategy approaches

The earliest CIs were single channel implants which were introduced in the 1970s. These included the House/3M and Vienna/3M devices. In these devices, a single 340 – 2700 Hz (House/3M) or 100 – 4000 Hz (Vienna/3M) band pass filter. Although this design preserved some temporal fine structure information, few users of single channel CIs achieved open set speech recognition, though they received benefit from the device as an aid to lip reading (Loizou, 1999).

The first multiple channel implants were introduced in 1984, which gave CI users a greater likelihood of effective speech perception than single channel implants (NIH, 1988; Wilson & Dorman, 2008). Early multichannel sound processing strategies attempted to simulate the input waveform with an electrical analogue. The early strategies comprised Feature Extracting Strategies, Compressed Analogue, and Simultaneous Analogue Stimulation.

A now obsolete category of strategies is the Feature Extracting Strategies. The earliest of these was the Nucleus F2/F0 strategy, which used an estimate of F2 (the second formant) to determine which one of 22 electrode to stimulate, and stimulated at a rate of F0 pps (Clark, 1987). Another early approach was the F0/F1/F2 strategy, in which the fundamental frequency and frequencies of the first and second formant were extracted from the input signal, with the latter two converted to positions on the electrode array (Gfeller et al., 1997). Feature Extracting Strategies were further developed by Cochlear in the 1980s and implemented commercially as MPEAK. A block diagram of the MPEAK strategy is shown in figure 1.12. In this strategy, higher frequency information was passed through three bandpass filters and envelope detectors, the output of which was assigned to electrodes at the basal end of the array.

Another early and now discontinued strategy was the Compressed Analogue (CA) strategy. A block diagram of the CA strategy is shown in figure 1.13. In this strategy, a fast-acting automatic gain control circuit either increased or reduced the amplification of the input sound to account for the speaker’s vocal effort and distance from the listener (Zeng, 2004). This was followed by a bank of four bandpass filters spanning the range of speech frequencies. The signal from each filter was compressed and directed to a corresponding electrode in the implant (Wilson, 2006).

The Simultaneous Analogue Stimulation (SAS) system was an improvement on the CA strategy. It was originally used in AB’s Clarion 1.0 device, though this has now been discontinued. As with the CA strategy, SAS made use of continuous waveforms for stimuli, rather than the biphasic pulses used in present approaches such as CIS (Wilson, 2006). In the SAS strategy all electrodes were stimulated simultaneously using bipolar electrode coupling. Each electrode was paired with another nearby electrode, which minimised the possibility of electrical interaction.

1.5.2 Pulsatile strategies and current approaches

Advances in sound processing strategies in the decades since the early strategies have brought about further improvements to the CI user’s experience of speech. Strategies in modern use utilise the output of a number of bandpass filters to estimate the envelope of the waveform, which is used to create stimuli which are presented to the electrode array in the form of electric pulses (McDermott, 2004). These approaches have produced improvements in speech perception, while other information such as voice pitch has received less attention (Green et al., 2004).

1.5.3 Continuous Interleaved Sampling

The most commonly used strategies in modern CIs are Continuous Interleaved Sampling (CIS) and n-of-m strategies (Wilson et al., 1995; McDermott, 2004). CIS is used by all major CI manufacturers, but in different implementations. In this strategy, the microphone input is subject to a pre-emphasis filter, the output of which is directed to a bank of bandpass filters. The temporal envelope is then extracted from each band. The envelope is compressed logarithmically so that the acoustic amplitudes are matched to the narrow dynamic range of the CI user (Zeng et al., 2008; Wilson, 2006). This set of compressed envelopes is then used to modulate a train of balanced biphasic pulses, which are delivered to each electrode, temporally offset to avoid overlap across channels (Wilson et al., 1995). A block diagram of the CIS processing strategy can be seen in figure 1.14.

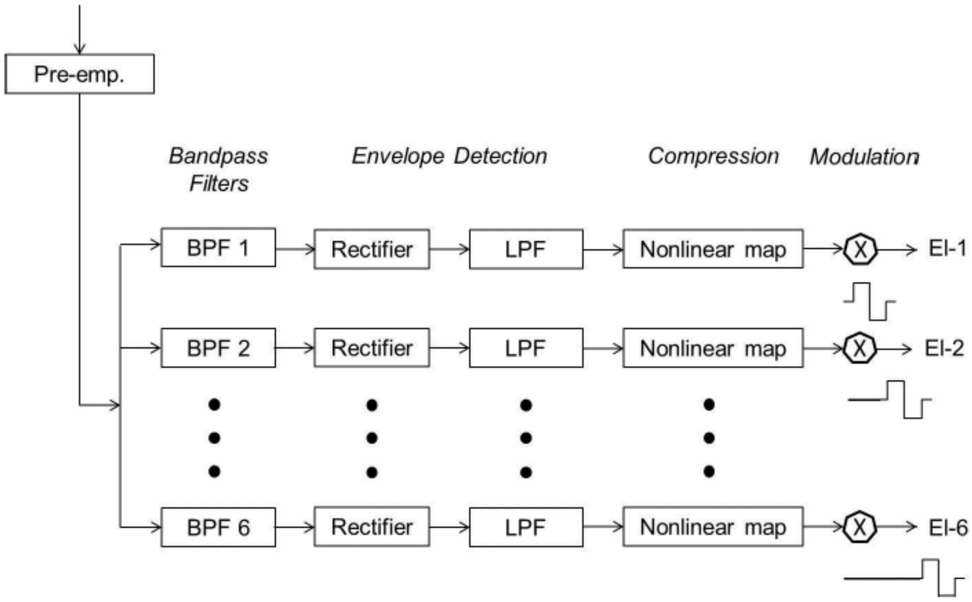


Figure 1.12: Block diagram of Continuous Interleaved Sampling processor, adapted from Loizou (1999) by Saleh (2013).

The CIS strategy has been shown to provide better speech recognition than CA. Wilson et al. (1995) compared 11 patients in their performance with the CA and CIS strategies in tests of consonant recognition and the open set tests of the Minimal Auditory Capabilities (MAC) battery (Owens et al., 1985). Patients were selected either because of their high or low performance with the CA processor. Both sets of subjects showed improvements for all tests, and one of the low performing subjects even achieved scores on the open set tests with the CIS processor that would have qualified him for membership in the high performing group with the CA processor.

Comparisons between CIS and SAS have also been carried out. In a study of vowel, sentence and consonant recognition by Loizou et al. (2003) individual results suggested poorer performance with SAS than with CIS. However, Battmer et al. (1999) show more positive results for SAS. They evaluated post-operative performance of 20 CI users fitted with both CIS and SAS. After three months, precisely half of the subject preferred CIS and half preferred SAS. Subjects performed best in their preferred strategy on tests of consonants and vowel recognition, although the SAS group's performance on speech in noise suffered a greater drop than the CIS group. Overall the availability of a choice in processing strategy led to better performance when compared to a previous group who only had access to CIS. This was however an early implementation of the CIS strategy using only eight channels at a low stimulation rate, which is different from modern implantations of the strategy.

Similar to CIS, the Paired Pulsatile Sampler (PPS) strategy involved the simultaneous stimulation of pairs of distant electrodes, with the pairs presented in a non-simultaneous sequence. It was otherwise identical to CIS, with double the rate of stimulation on any one electrode. The simultaneous stimulation of pairs of electrodes distant from each other was intended to minimise interactions between the electrodes (Wilson, 2006).

1.5.4 N-of-m

CIS shares a number of features with another group of strategies known as n-of-m. These features include non-simultaneous stimulation and high cut-off frequencies for the envelope detectors (Wilson, 2006). Similar to CIS, n-of-m involves stages of bandpass filters (though a greater number than CIS) and envelope extraction. The n (out of m) channels with the largest envelope amplitude are selected prior to each frame of stimulation across electrodes. The electrodes which correspond to the n channels are the only ones to be stimulated (Zeng et al., 2008; Wilson, 2006).

The oldest available version of this system is in the Spectral Peak (SPEAK) strategy in the Cochlear Nucleus 22 system, in which n depends on the sound signal and may vary from one stimulus frame to the next. The 6 to 8 largest peaks are selected at a fixed 250Hz per channel rate (Zeng et al. 2008). The newer Nucleus 24 system utilises ACE (Advanced Combination Encoder), in which n is a constant number for each cycle and the stimulation rate is higher (Ziese et al., 2000). If n and m are equal, then SPEAK and ACE are equivalent to CIS (Zeng et al., 2008). A block diagram of the ACE system can be seen in figure 1.15.

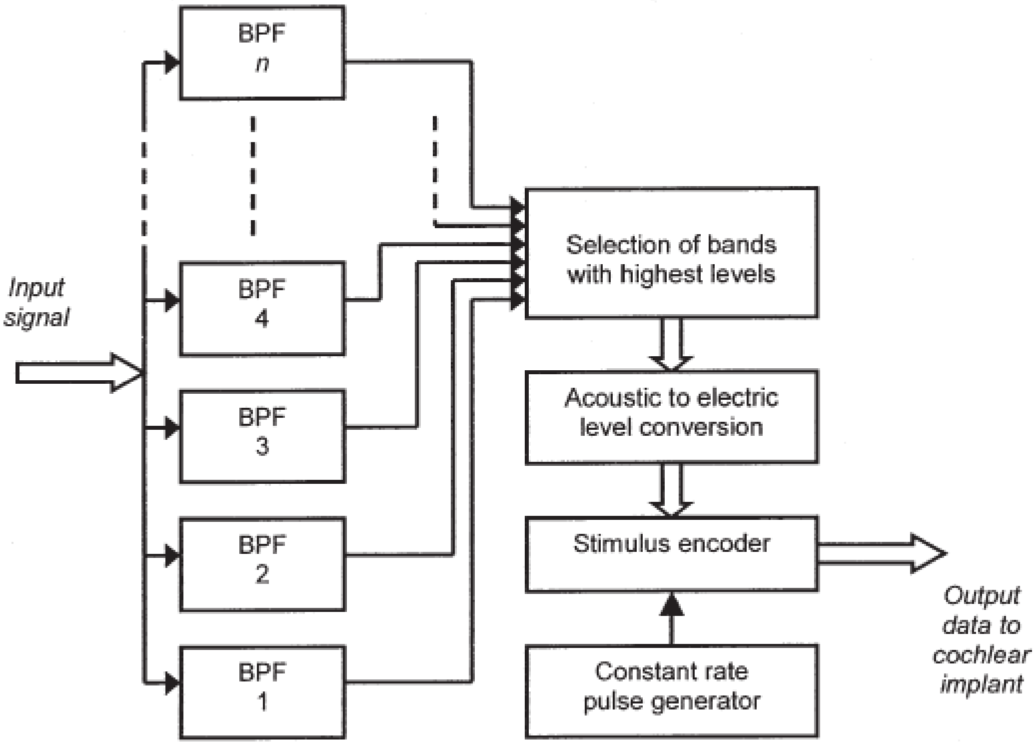


Figure 1.13: Block diagram of the ACE processor, taken from McDermott et al. (2004)

Ziese et al. (2000) compared 12 channel and 7 channel CIS processors with a 7 of 12 n-of-m strategy used in the MED-EL COMBI 40+ system. The participants' perception of a number of speech elements was tested, inclding vowels, consonants, monosyllables and sentences in quiet and sentences in noise. The strategies performed equally well for consonants and sentences in quiet, and for monosyllables n-of-m was significantly better. Sentence understanding in noise was also equivalent across all three strategies.

Donaldson and Nelson (2000) used a consonant recognition task to examine place-pitch sensitivity in users of MPEAK and SPEAK. Users accustomed to MPEAK and who were tested to have good place-pitch sensitivity were trained on SPEAK for a period of one month. Testing on both strategies after this period, all but one participant performed poorly in consonant place-cue identification, despite the improved spectral representation in SPEAK. Testing only with participants accustomed to SPEAK did however show a positive relationship between place-pitch sensitivity and consonant recognition.

The interlacing of stimulus pulses across electrodes is a key feature of CIS, n-of-m, ACE and SPEAK, eliminating an element of interaction between electrodes. The strategies utilise a relatively high cut-off frequency for the lowpass filters in the envelope detectors, generally in the range of 200-400Hz (Wilson, 2006).

1.5.5 ‘Virtual Channel’ sound processing strategies

Early research in CI pitch perception revealed that adjusting the proportion of current delivered simultaneously to two electrodes may cause intermediate pitches to be perceived (Townshend et al. 1987). This technique is termed ‘current steering’ and the additional pitch percepts are known as ‘virtual channels’ (Firszt et al., 2007). Townshend et al. (1987) first showed that simultaneous stimulation of non-adjacent electrodes can produce intermediate pitch percepts. Virtual channels resulting from sequential stimulation have also since been demonstrated. Wilson et al. (1992) developed the virtual channel strategy as a refinement of the commonly used CIS strategy, and showed that pitch perception could be manipulated by both simultaneous and nonsimultaneous stimulation of adjacent electrodes. McDermott and McKay (1994) carried out a study in which two biphasic pulses, separated by 0.4ms, were delivered sequentially to two intracochlear electrode pairs, and demonstrated the perception of intermediate pitches.

A virtual channel strategy has been implemented by AB in their HiRes 120 speech processing strategy. Using independent current sources, this strategy presents biphasic pulses to up to 16 electrodes using monopolar stimulation (Wilson, 2006). It creates eight additional intermediate stimulation sites between each electrode pair, by varying the proportion of current delivered simultaneously to the pair, offering 120 potential stimulation sites (Brendel et al., 2008). A schematic representation of the HiRes 120 strategy can be seen in figure 1.16.

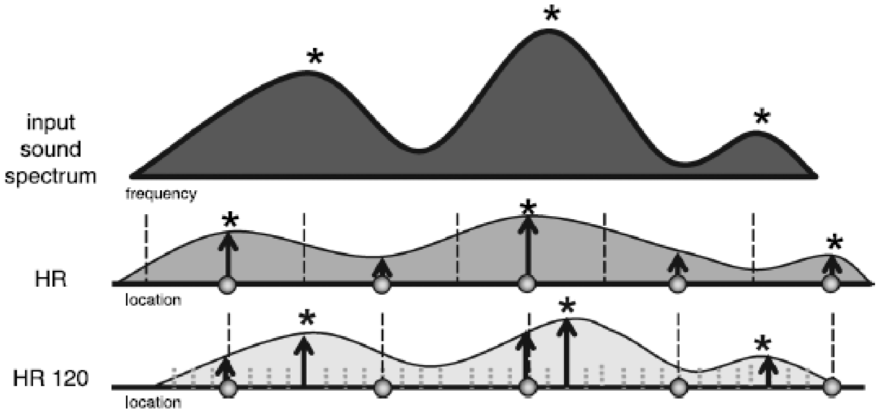


Figure 1.14: Schematic representation of an input stimulus frequency spectrum and corresponding stimulation with either HiRes or HiRes 120, taken from Firszt et al. (2009).

Donaldson et al. (2005) carried out a study involving users of the HiRes strategy, with the aims of estimating the number of discriminable distinct pitches in dual electrode stimulation, and examining the effects of current level on place-pitch discrimination and loudness. Six adults were tested using the Clarion CII device which had 16 electrode contacts. Biphasic pulses were presented to electrodes in apical, middle and basal positions on the electrode array (electrodes 2 and 3, 7 and 8, and 12 and 13). Electrodes were stimulated both singly (the more apical of the pair) and dually (both electrodes of the pair). Proportion of current to the more basal electrode in dual-electrode stimulations ranged from 0 (all to apical) to 1 (all to basal). The study followed a two alternative forced choice procedure with participants asked to identify the higher sound (to be scored correct this had to be the dual electrode interval). Stimuli were balanced in loudness to either medium loud or medium soft perceptual level. Place-pitch discrimination thresholds and equal-loudness levels were also determined using an adaptive task. Results showed considerable variability in place-pitch thresholds across subjects and electrodes. Medium loud stimuli generally produced greater place pitch sensitivity. Dual electrode stimuli required higher current levels than single electrode stimuli for equal loudness, though the absolute magnitude of these differences was small. The number of discriminable intermediate pitches was estimated at two to nine, owing to the range of current proportion thresholds of 0.11 to 0.64.

Firszt et al. (2007) aimed to extend the results of Donaldson et al. (2005) in determining the number of spectral channels available using current steering. They tested 106 adults in a multi-centre study using either CII or 90K implant systems. Initially they performed loudness balancing and pitch ranking of electrode pairs 2 and 3, 8 and 9, and 13 and 14. In the following ‘Near’ experiment, participants were asked to compare Stimulus A (100% of current to the more basal electrode) and Stimulus B (current varied between the electrode pair). In the ‘Centre’ experiment, Stimulus A involved 50% of current to each electrode in a pair, and Stimulus B varied the proportion of current between the two contacts. The mean number of virtual channels discernible were 5.3 for the apical pair (electrodes 2 and 3), 6.0 for the middle pair (electrodes 8 and 9), and

3.8 for the basal pair (electrodes 13 and 14). 45% of participants were able to discriminate 2 or more intermediate channels on the apical and middle pairs, and 28% for the basal pair. The authors deduced that the place-pitch capabilities of CI users is greater than previously thought.

Despite being limited by the fact that they used only single, spectrally narrow stimuli, the above studies demonstrate that HiRes 120 and the ‘virtual channels’ approach to sound processing may present opportunities for a much greater range of pitch percepts than standard implementations of CIS, although further investigation with wide-band spectrally complex stimuli is warranted to give a fuller picture of the possibilities of HiRes 120.

1.5.6 Fine Structure Processing

Other CI companies besides AB have claimed to utilise virtual channels to improve pitch perception in their speech processing strategies. One such is MED-EL, whose Fine Structure Processing (FSP) strategy is designed to convey fine structure information which is crucial to pitch perception, and has been shown to be the primary information carrier for music perception (Smith et al., 2002). In the FSP strategy, the lower channels utilize channel specific sampling sequences. Each of these sequences is a series of stimulation pulses which has an instantaneous repetition rate equal to the instantaneous fine structure frequency of the signal in that frequency range (Hochmair et al., 2006). The remaining channels employ a sequential implementation of the so-called virtual channel strategy. Non-simultaneous stimulation has been shown to create neural level interactions due to shared areas of excitation (McDermott & McKay, 1994).

A number of studies have been carried out which compare CIS to FSP. Arnoldner et al. (2007) compared CIS and FSP on measures of speech and music perception in fourteen CI users. Subjects were tested first with their familiar CIS processor and at four subsequent visits with FSP. There was an improvement in mean speech recognition results for all participants between their baseline visit and 4th FSP visit, particularly for speech in noise. Significant improvements were also seen in tests for perception of musical rhythm, melody and timbre. However, this study did not control for learning effects, and a later study by Magnussen (2011) found no significant difference in speech intelligibility and music sound quality between the two strategies, though nearly half their participants preferred FSP for listening to speech. It is possible that the availability of a choice between processors produces better results than being restricted to just one (Arnoldner et al., 2007).

1.5.7 Summary

Up until the early 1980s, many believed that CIs would provide no more to HI people than an aid to lipreading. Advances in CI sound processing strategies have led to over a quarter of CI users being able to achieve perfect marks on standard sentence recognition tests (Gifford et al., 2008). Table 1.2 gives an outline of the names of the processing strategies in current use by the three major CI manufacturers.

Table 1.2: Processing strategies in use by the three major CI manufacturers. ACE and SPEAK are different implementations of the n-of-m strategy.

Manufacturer	CIS	n-of-m	FSP	ACE	SPEAK	HiRes	HiRes 120
MED-EL	▨	▨	▨				
Cochlear	▨			▨	▨		
Advanced Bionics	▨					▨	▨

Music, however, remains challenging for many CI users, as they do not receive the fine structure information which is crucial to pitch perception. Pitch is a vital aspect of music, particularly in melody and harmony. It is possible that improvements to pitch perception provided by sound processing strategies which utilise virtual channels, or which deliver more fine structure information, may improve CI users' perception and enjoyment of music. The next section will describe the difficulties faced by CI users when listening to music.

1.6 Listening to music with a cochlear implant

Adult CI users often indicate that they are dissatisfied with their perception of music through their CI. Various questionnaire studies have revealed that up to a third of CI users do not enjoy listening to music with their implants (Leal et al., 2003, Gfeller et al., 2000). Enjoyment of music is often reported as vastly decreased when compared to before loss of hearing, with between 40% and 86%

reporting music to be worse (Gfeller et al., 2000, Leal et al., 2003) and enjoyment scores dropping by 61% (Mirza et el., 2003). The regularity of music listening activities decreases after implantation, with one study showing less than half of participants listening to music at all (Mirza et al., 2003, Lassaletta et al., 2008). It is therefore important to address the question of why music perception is so much less satisfactory for CI users than speech perception is.

The main consideration for CI processing strategies is to provide speech perception and awareness of environmental sounds (Wilson, 2006; Tyler et al., 2000). To this end the focus has been on accurately delivering the envelope cues, which are the slow fluctuations in level which are known to be important for speech understanding, in particular the manner, rhythm and syllabic content of speech (Schauwers et al., 2012) The rapid fluctuations, the fine structure, are important for pitch perception, cuing place of articulation, voicing and voice quality (Rosen, 1992, Schauwers et al., 2012)**.** Temporal fine structure is typically not provided in current day processing strategies, and thus pitch perception is largely dependent on the number and location of the electrodes in the electrode array.

Many adult CI users report a desire for improved music perception, with several studies rating music perception as the most important aspect of hearing for CI users after speech perception (Stainsby et al., 1997; Gfeller et al., 2000). The different CI manufacturers have devised strategies with different methods of improving the delivery of pitch information. MED-EL addressed loss of fine structure information in their FSP strategy (Arnoldner et al., 2007), and AB tackled the limitations of the electrode array using virtual channels in the HiRes 120 strategy (Donaldson et al, 2005; Firszt et al, 2007). It may therefore be expected that CI users with devices from these two manufacturers may receive the most benefit in terms of pitch perception relative to other manufacturers. In the sections to follow, the literature concerning different aspects of pitch perception in CI users is reviewed.

1.6.1 Pitch perception with a CI

For a CI user, spectral information is provided by differences in current across the electrodes. Therefore information relating to place pitch is limited by the number and location of the physical electrode contacts available for stimulation. Temporal information is limited by the sound processing strategy, which in many cases removes the temporal fine structure cues. In a study examining the differing contributions of place and temporal information to pitch perception in CI users, Zeng (2002) measured changes in FDL for pitch encoded in rate of stimulation on a single electrode pair. It was demonstrated that temporal pitch cannot be discriminated by CI users at rates higher than 300 Hz.

Studies looking at music perception through CIs have shown that although slower, time-related aspects of music, such as tempo or rhythm, are relatively well preserved, the recognition of pitch is difficult. Experiments looking at frequency difference limens in CI users have revealed large individual differences, but in general poorer performance than NH listeners (McDermott, 2004). As detailed in section 1.2, meaningful differences in music occur with a pitch change of approximately 6%, which is one semitone. A number of studies with NH listeners have shown that they are reliably able to pitch rank sounds that differ by one semitone (Schulz & Kerber, 1994; Gfeller et al., 2002). Several studies have shown that a difference this small can however be difficult for CI users to perceive (Fujita & Ito, 1999; Galvin et al.; 2007, Looi et al., 2008)

In a pitch ranking task performed both by CI users and NH listeners, it was shown that while the mean difference limen for NH participants was 1.13 semitones, CI users averaged a 7.56 semitone difference limen, and performance amongst the participants with CIs varied greatly, with individual difference limens between one and 24 semitones (Gfeller et al., 2002). A later study which compared the abilities of CI and NH listeners to rank the pitches of sung vowels found that CI users performed at chance when asked to rank a one semitone difference (Sucher & McDermott, 2007). Identifying melodic patterns also becomes more difficult when the interval between notes is only one semitone (Galvin et al., 2007).

A comparison between the abilities of CI users and hearing aid users with similar hearing loss profiles to rank the pitches of sung vowel stimuli showed significantly better results amongst the HA users, who performed above chance when they were pitch ranking differences of one, half and a quarter of an octave (that is, 12, 6 and 3 semitones, respectively). At the 3 semitone difference, CI users were no better than chance (Looi et al., 2008). A further study using the same tests assessed CI users both before receiving the implant (while using an HA) and three months post-implantation. Results were similar to the previous study with significantly worse performance on the task with the CI (Looi et al., 2008b).

Fujita and Ito (1999) tested eight participants in a pitch ranking test, using intervals of 2, 4, 8, 10 and 12 semitones, requiring the participant to identify the higher of the two. While five participants could distinguish intervals between 4 and 10 semitones, three were unable to distinguish even the 12 semitone (one octave) interval. Electrode placement or inconsistent neural survival may also cause pitch reversals to occur, regions where quality of the sound is distorted, or uneven steps in pitch change due to poor electrode differentiation. This can affect the tonotopic nature of the pitch map and the sensitivity to pitch changes (Vandali et al., 2005; Finley and Skinner, 2008; Saleh, 2013). Such perceptual issues can make the recognition and enjoyment of a melody very difficult.

Other studies have looked at different factors which may have an impact on the CI music listening experience, such as number of channels of information. Different speech stimuli have been shown to be optimally transmitted with different numbers of channels, such as in the case of vowels, which require more channels than sentences (Dorman et al., 1997). Friesen et al. (2001) found that users of the Nucleus CI did not achieve any addition benefit to speech in noise perception when the number of channels was increased beyond eight. Tyler et al. (2000) found that listeners accustomed to eight channels preferred their music listening experience when compared to listening with only one channel, while changes in the rate of stimulation had no effect. This may be due to the increased number of pitch percepts available with more channels, providing increased perception of melody and harmony. NH subjects listening to familiar melodies in simulations of CI hearing have been shown to need up to 32 channels to recognise a melody in the absence of rhythmic cues (Kong et al., 2004).

The above studies have shown that while there is a great deal of individual difference amongst CI users in terms of their pitch perception abilities, they do consistently fall below the performance of NH listeners. With pitch differences being a crucial component of a melodic sequence, it is not surprising that given their difficulties with pitch perception, the perception of melodies is also a very difficult area for CI users.

1.6.2 Melody perception with a CI

Galvin et al. (2007) tested eleven CI users with a melodic contour identification task. The participants heard one of nine five-note melodic patterns and selected which one they heard from a computer screen. These patterns had one of three root notes (A3, A4 or A5) and successive intervals within the patterns ranged from 1 to 5 semitones. Mean performance when the intervals were 5 semitones apart was 64.2%, but when there was only a one semitone interval in the sequence, this dropped to 31.8%. Mean performance on the same task for NH subjects was 94.8% across all conditions. In the same study a familiar melody identification task was also carried out, in which participants identified one of twelve familiar melodies presented with or without rhythm cues. Mean performance in this task dropped from 60.1% with rhythm cues to 28.2% without.

Pressnitzer et al. (2005) carried out a melody task with NH and CI participants. First, each participant’s pitch ranking ability was assessed, revealing that the CI users could pitch rank at differences between 2 and 7 semitones, whereas the NH control group could pitch rank down to 0.2 of a semitone. In the experimental task, a four note chromatic melody was presented twice, with one note changing in the second presentation. Identifying the changed note proved impossible for most CI users, even when the interval between the changing notes was larger than each individual listener's pitch ranking threshold. The NH control group performed at ceiling.

Given their impairments in pitch recognition, many CI users rely on other cues such as lyrics or rhythm in order to recognise tunes. Various studies (Schulz and Kerber, 1994; Gfeller et al., 2002) support the idea that rhythmic information is important in the recognition of melodies. Kong et al. (2004) tested CI users and NH listeners on the recognition of monophonic melodies with and without rhythmic cues. Stimuli were two sets of twelve songs which were familiar to the participants. NH participants achieved near perfect scores on both conditions. They recognised 97.5% of melodies in the no-rhythm condition, whereas CI users performed at chance for that condition, and were worse than NH listeners in the condition with rhythmic cues, averaging 63.2% correct compared to 98.3% correct for the NH listeners.

Closed-set melody recognition with lyrical or rhythmic cues has also produced better results. Fujita and Ito (1999) found that verbal information was more important than pitch, rhythm or tempo in the recognition of well-known nursery songs. Lyrical cues were also shown to be important in Leal et al.'s study (2003). In a similar test of nursery song recognition, only 3% of 29 participants were able to recognise half or more of the songs in a melody only condition, but this rose to 96% when verbal cues were available. While pitch perception is a key factor in the enjoyment and perception of music, it may be the case that with musical training pitch perception can be improved. Chen et al. (2010) trained 27 pre-lingually deafened children with pitch perception and discrimination tests, and found that duration of training positively correlated with rate of correct answers on the pitch perception test.

1.6.3 Recognition and perception of multiple pitches with a CI

Only a handful of studies have so far looked into the perception of simultaneously presented tones in CI users (Donnelly et al., 2009; Penninger et al., 2013, 2014). In these studies, listeners were presented with a number of simultaneous tones, with a task of identifying the number of separate pitches in the stimulus. The first of these studies used both pure tones and piano tones presented acoustically (Donnelly et al., 2009). Twelve post-lingually deafened CI users and twelve NH controls listened to stimuli which consisted of one, two or three simultaneous tones. The NH group performed significantly better at identifying that a stimulus contained multiple pitches than CI users, although they were more likely to identify three pitch stimuli as two pitches. The CI group performed at near chance levels for identifying two and three pitch stimuli, often reporting them as one pitch. Identifying a tone as containing multiple simultaneous pitches when presented acoustically clearly presents difficulties for CI users.

Penninger et al. (2013) carried out similar experiments using direct electrical stimulation. Stimuli consisted of biphasic pulse trains of one modulation frequency, applied to either a basal, middle, or apical electrode; or of two modulation frequencies, either both on an apical electrode, or one on an apical and one on a middle or basal electrode. Contrary to the previous study by Donnelly et al. (2009), participants scored significantly above chance at identifying the number of tones in the stimulus. A further study added stimuli consisting of three simultaneous pitches (Penninger et al., 2014). In this study, the one pitch stimuli were applied to a basal, a middle or an apical electrode; two pitch stimuli were applied to basal plus apical, middle plus apical, or basal plus middle; and three pitch stimuli were presented simultaneous on basal, middle and apical electrodes. Participants were again significantly above chance at identifying stimuli as containing one, two or three pitches.

The results of Penninger et al. (2013, 2014) show better capabilities in their subjects to recognise the presence of multiple pitches than seen in in the study by Donnelly et al. (2009). However, most often the music CI users will actually hear will be presented acoustically. Further investigation into the perception of acoustically presented simultaneous tones for CI users could give insight into how this important aspect of music can be made more accessible.

1.6.4 Pitch perception in children with CIs

Most research into pitch perception in CI users has been carried out with adults. Studies that have been carried out with children as participants have shown that although children with CIs generally outperform adults with CIs, they do not perform as well as NH children (Looi & Radford, 2011; Looi, 2014; Edwards, 2013). Children with CIs have difficulty recognising familiar melodies (Nakata et al., 2005; Volkova et al., 2014), recognising emotions in music (Hopyan et al., 2011; Shirvani et al., 2014) and in ranking one pitch as higher than another (Looi, 2014). Despite this, some studies have shown that children with CIs are more likely to report enjoyment of music than adults with CIs (Nakata et al., 2005, Shirvani et al., 2014). Pitch and music perception in children with CIs is examined more fully in chapter 5.

One study carried out with children that is important to the present research is that by Vongpaisal et al. (2006). This study used musical chords to test CI listeners' ability to discern a one semitone pitch change within a melodic sequence. As discussed in the previous section, NH listeners are generally able to distinguish between semitones, and some NH listeners are able to discriminate frequency differences far smaller than a semitone (Dallos, 1996). Eight CI listeners from age 6 to 19 years, and thirteen NH 5 year olds took part. They were presented with two sequences for comparison, each starting from the note known as middle C or C4, with a frequency of 262 Hz. The C major triad (sequentially as C4-E4-G4-E4-C4) was either presented twice, or alongside C minor (C4-E♭4-G4-E♭4-C4) or C augmented (C4-E4-G♯4-E4-C4). In each comparison, the possible difference between sequences amounted to just one semitone. Participants had to judge whether the sequences were the same or different. There was a significant difference between the two groups, with the NH children performing well above chance, whereas the CI users were at or below chance level on all comparisons.

1.7 The present research

The principle aim of the research detailed in this thesis was to examine pitch perception in musical contexts in CI users. Musical chords were chosen as the component of music with which to examine pitch perception due to a number of characteristics they possess. Firstly, the study by Vongpaisal et al. (2006)

showed that the perception of small, important differences between two musical chords may be difficult for CI users. Chords are a prevalent feature of Western music, and a music listener with a CI is likely to encounter chords in one form regardless of which genre of music they choose to listen to. However, there have been very few studies looking at the perception of musical chords in CI users.

Secondly, chords are a unique aspect of music in that they retain their essential character regardless of whether they are varied in a number of ways. The notes of a chord can be played simultaneously or sequentially without altering the chord. For example, a C major chord remains a C major chord regardless of whether its notes are played together or successively as an arpeggio. The same cannot be said about, for example, a melodic phrase. The opening notes of "Happy Birthday" are instantly recognisable as a melody, but if the notes were played simultaneously, they would no longer represent the song from which they came. In the work of Vongpaisal et al. (2006) they examined the perception of musical chords only in an arpeggiated or sequential presentation; however, the simultaneous sounding of notes is a central character of Western music (Taylor, 2000). Therefore, in the present research, a chord discrimination test was devised which uses musical chords presented simultaneously and sequentially to examine pitch perception abilities of CI users, allowing an examination of pitch perception in both melodic and harmonic contexts. Similarly, the notes of a chord can vary over a number of octaves without changing the essential nature of the chord, allowing for pitch perception in different spectral regions to be examined. Therefore, using musical chords as a basis for examining pitch perception in musical contexts allows for the examination of a number of parameters in order to discover which aspects are important for pitch perception for CI users.

Previous studies have shown that CI users have reported vastly decreased enjoyment of music in CI users compared to prior to hearing loss, as well as a decrease in music listening habits (Gfeller et al., 2000; Leal et al., 2003; Mirza et al., 2003; Lassaletta et al., 2008). Objective measures of pitch perception can provide information regarding the smallest differences in pitch that an individual can perceive, but this may not correspond to the individual's subjective experience of music (Gfeller et al, 2008). A questionnaire study was carried out in order to gain a more complete understanding of CI users' enjoyment of music in the present day, what factors might impact this, and how it might relate to their perception of pitch.

Another aim of this research was to examine the relationship between CI users' pitch perception in musical contexts and speech perception, which is what CI processors are optimised for (Wilson & Dorman, 2008). Many CI users are able to achieve high levels of speech perception, especially in quiet (McDermott, 2004). However, this may not necessarily correspond to high levels of pitch perception. CIs are designed for more accurate representation of the temporal envelope of sounds which is known to be important for speech understanding at the expense of fine structure, which is important for pitch perception (Rosen, 1992, Schauwers et al., 2012). By carrying out speech perception tests alongside the Chord Discrimination Test, comparisons could be made between results on both tests.

A final aim was to examine pitch perception in musical contexts for children who are CI users. Most CI research looking into pitch and music perception has been carried out with adults. Children who have been implanted pre-lingually will have little to no experience of music with normal hearing. They are more likely than adults with CIs to report enjoying listening to music (Nakata et al., 2005, Shirvani et al., 2014). Previous studies have shown that in pitch ranking tasks, children with CIs outperform adults with CIs (Looi & Radford, 2011; Looi, 2014). Vongpaisal et al. (2006) found that identifying small changes in musical chords was difficult for CI users who were children or teenagers, but a comparison with adults' abilities was not made. The present research addressed that gap in the research literature by comparing the performance of adults and children at discriminating small differences in musical chords.

In examining music appreciation in adult CI users, and pitch perception in musical context for adults and children using CIs, the main questions addressed by this research were as follows:

1. What is the current level of enjoyment and appreciation of music that CI users are able to experience, and is this linked to their abilities on objective pitch perception tests?
2. What are the parameters which may affect pitch perception for CI users in a musical context?
3. What is the relationship between CI users' pitch perception and speech perception abilities?
4. Are adults and children who hear with CIs able to discriminate small differences in musical chords?

1.7.1 Outline of chapters

The following chapter, chapter 2, looks at the music experience and enjoyment in current day CI users based on questionnaire results. Chapter 3 describes a pilot study carried out to evaluate and optimise musical parameters to be tested in the main study. Chapter 4 reports on the main study which used the optimised tests based on simulated piano tones and sinusoids and with Presentation, Chord Change and Chord Root parameters to explore pitch perception in a musical context. In addition results were compared to the participants' pitch ranking ability and speech perception abilities. In chapter 5 a version of the chord discrimination test was developed for assessing pitch perception abilities in young children. This test was piloted, refined and re-run with a group of children participating in a singing study, and results were compared to other measures of speech perception abilities. Chapter 6 contains the final discussion and concluding remarks.

Chapter 2 – Experience and enjoyment of music for cochlear implant users: questionnaire piloting and validation

2.1 Introduction

Hearing-impaired patients who receive a CI often report improvements to many aspects of their life. Mäki-Torkko et al. (2015) conducted a questionnaire study looking at 120 CI users' expectation prior to their surgery compared to the reality of their experience with the implant. They found positive reports on several factors including improving their ability to enjoy a social life, greater autonomy and less reliance on loved ones, and a greater sense of normality in their life. One expectation for improvement that was not met for many who responded to the questionnaire, however, was listening to music.

An individual's experience and enjoyment of music is a personal and subjective thing. Quantitative measures of pitch discrimination are informative with respect to understanding the minimal differences that an individual can perceive, but to truly understand how these perceptual limitations affect an individual, qualitative measures of subjective experience are required**.** Previous research has suggested that there may not be a straightforward relationship between objective measures of a CI user's music perception, and their subjective enjoyment of music (Gfeller et al., 2008). Questionnaires and interviews are better tools for examining subjective experience of music than formal assessments of psychophysical abilities.

A number of questionnaire studies looking at CI users' subjective experience of music have been carried out over the last two decades. Many of these studies have reported a disappointing music listening experience for CI users, with two studies reporting that a third or more of respondents found no enjoyment in listening to music with their CI (Leal et al., 2003; Gfeller et al., 2000). No one sound processing approach has thus far been shown to provide the best results for music enjoyment (Looi, 2008). In one study, 29 CI recipients were tested on speech and music perception as well as responding to a questionnaire examining their musical background, listening habits and level of musical experience. For 86% of respondents, reduced musical listening experience with their implant was reported compared to prior to going deaf, and 38% did not enjoy listening to music at all (Leal et al., 2003)

Fredrigue-Lopes et al. (2015) administered the Munich Music Questionnaire (MUMU) to 19 adult CI users. The number of participants who reported listening to music often or always dropped from 14 when referring to the period before hearing loss, to 6 during CI use. The number of participants listening to music for more than an hour a day dropped from 13 before hearing loss to 6 with CI. However, those who found music to be very important to their lives before hearing loss still felt as strongly about music with the CI.

Mirza et al. (2003) administered a questionnaire to the 60 patients who had been implanted between 1990 and 2000 by the North East Cochlear Implant Programme in Middlesbrough, UK. Responses were given by 35 of these CI users, the remainder either declining or excluded to due illness, death or relocation. Results showed that less than half of the respondents listened to music after implantation, and overall scores for enjoyment levels dropped from 8.7 out of 10 before deafness to 2.6 out of 10 after implantation. Those listening to music post CI switch-on were more likely to be younger, have higher speech recognition scores and shorter duration of deafness. It is worth noting the impact of duration of deafness, as a long period of deafness without listening to music may lead to decreased inclination to listen to music post-implantation, due to a decreased recognition and memory for music.

Other studies have sought to discern factors which may contribute to the level of enjoyment a CI users is able to obtain from music. Length of implant use has not been found to have an effect on enjoyment of music (Gfeller et al., 2000). Users of bilateral CIs have reported greater music enjoyment than those with a unilateral CI, though still less than NH listeners (Veekmans et al., 2009). Lassaletta et al. (2008) combined questionnaire data with music perception test scores, and found no significant association between enjoyment of music with an implant and a wide variety of potential predictive factors. These included duration of deafness, length of CI use, speech perception results, and musical background. Overall their participants showed a decrease in music listening activities post CI, with the percentage of respondents listening to music for only two hours or less per week almost doubling with the CI, rising from 32% to 62%.

The amount of time a CI user devotes to listening to music may have an impact on their ability to enjoy it. Gfeller et al. (2000) found that 23% of a sample of 65 adult CI users reported little satisfaction in music listening both before (when profoundly deaf) and after CI implantation. The same proportion reported music to be as good as before hearing loss, but almost double that amount (43%) found it to be worse than before hearing loss, although they noted an improvement over time. A significant correlation between enjoyment of music and length of time spent listening to music post implantation was found. However, it is not clear whether more time spent listening to music led to greater enjoyment, or that those who already enjoyed music more spent more time listening to it.

Some researchers have found that training in active listening to melodies has also been shown to have a positive impact on both recognition and appreciation of music (Gfeller et al., 2002). Looi and She (2010) carried out a questionnaire study looking at the music listening experience of 28 CI users, with an aim of devising a music training program which would encourage CI users to listen to music and appreciate it more fully. Mean scores for music enjoyment dropped from 8.4 out of 10 prior to hearing loss to 5.2 out of 10 with a CI. Ranking amount of time spent listening to music from 0 (never) to 10 (very often), scores dropped from 7.2 before hearing loss to 4.6 with CI. While 73% identified specific tunes they were always able to recognize, this leaves over a quarter of respondents with no tunes at all that they found recognizable. CI users were asked to identify the aspects they considered important for inclusion in a music training program for CI users, and by far the most important was training to improve the ability to recognize previously known tunes.

Training may also help to improve CI users’ perception of the timbre of a sound, which is another component that could help to effectively perceive and enjoy the sound made by a musical instrument. The sound quality of musical instruments is reported by CI users as less pleasant than NH listeners report (Gfeller et al., 1997; Looi, 2008). The definition of timbre is "that attribute of auditory sensation in terms of which a listener can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar" (Acoustical Society of America, 1960) and is represented by the spectral envelope (Gfeller et al., 2002). Several studies have shown that CI users are impaired compared to NH listeners in their ability to recognize musical instruments, particularly when there is little contrast between the sounds of the instruments, or when the instruments are heard in combination with others (Fujita & Ito, 1999; Looi, 2008; Kim et al., 2015). However, training may improve the experience of the sound of musical instruments for CI users. Driscoll et al. (2009) conducted a study in which 66 NH adults listened to CI simulations of eight different musical instruments. Training occurred under three conditions: repeated exposure; repeated exposure with feedback; and direct instructions, and accuracy of instrument identification was measured over seven weeks. Participants who received training by direct instruction and by feedback improved significantly in their instrument recognition by the end of the training.

Overall, these questionnaire studies have shown that CI users are often disappointed by their musical listening experience. There is a great deal of individual difference, but CI users typically report a diminished enjoyment of music following implantation, and a reduced amount of time spent listening to music. However, these studies have only included participants who were post-lingually deafened. Having lost their hearing in adulthood, these participants have a memory of what music sounded like with normal hearing. Studies have shown that late implanted, pre-lingually deafened adults can achieve improvements in speech perception and quality of life measures (Wooi Teoh et al, 2004; Klop et al, 2007), although their speech perception falls below that achieved by post-lingually defended CI users (Wooi Teoh et al., 2004). Pre-lingually deafened children who have received implants have reported greater enjoyment of music than post-lingually deafened adults (Fuller et al., 2013). However, a comparison of music appreciation between pre- and post-lingually deafened adults has so far not been made.

The questionnaire study detailed in this chapter was carried out with the aim of attaining a background of information regarding CI users' subjective experience of music in the present day. The goal of the study was to devise a comprehensive questionnaire for assessing current day CI users' subjective music listening experience, including how frequently they listen to music, how much they enjoy it, and whether they participate in other musical activities such as singing and playing instruments. Also examined were factors which may affect music listening experience for CI users, such as the device, age at hearing loss, age at receiving CI and duration of deafness. A further goal was to address the gap in the literature regarding music appreciation in pre-lingually deafened adult CI users, and to ensure that the mixture of respondents was representative of a wider demography than previous studies, which have largely focussed on the experiences of post-lingually deafened adults.

2.2 Phase 1: Questionnaire validation

A questionnaire validation study was conducted using the Mirza et al. (2003) questionnaire to validate and optimise it to ensure clarity and that the appropriate categories were covered. This particular questionnaire was selected for validation for three reasons. Firstly, it was easily accessible because it was made available in the Mirza et al. (2003) paper. Secondly, its questions covered music listening habits and musical playing and proficiency, thus providing details on musical background and experience of the participants. Finally, unlike for example the MUMU which was created by MED-EL, this questionnaire was not devised with any particular device in mind, and its questions were therefore applicable to all CI users regardless of device type.

2.2.1 Materials and methods

Ethics approval was given by the UCL ethics committee (UCL Ethics Project ID Number: 3523/001 for the pilot phase and 3523/003 for the main phase) prior to data collection for this study.

2.2.1.1 Mirza et al. (2003) questionnaire

The questionnaire from Mirza et al. (2003) comprised 27 questions, and included a combination of multiple choice, yes/no, value rating, and free text questions. The questions related to music enjoyment, listening and participation before going deaf, and with a CI.

2.2.1.2 Participants

Participants were recruited from a group of CI users who had registered interest in taking part in experiments at the UCL Ear Institute. Sixteen adult CI users completed the questionnaire. They ranged in age from 32 to 77 years old.

Thirteen were female and 3 male. Table 2.1 details the variety of devices used for each participant.

Table 2.1: Sound processor, sound processing strategy, age at testing and duration of CI use for the 16 questionnaire responders. Unavailable information is marked U. AB stands for Advanced Bionics, FSP refers to Fine Structure Processing and ACE to Advanced Combination Encoder. For ease of reference, the same participant numbers are used as for the pilot chord test study described in chapter 3. Therefore, participants 1 and 7 are omitted, as they did not participate in the questionnaire validation.

Participant	Gender	Sound processor	Sound processing strategy	Age	Duration of CI use
P02	F	Cochlear Freedom	ACE	69	5 years
P03	F	MED-EL Opus 2	FSP	60	2 years
P04	F	Cochlear Nucleus 5	ACE	53	2 years
P05	F	Cochlear Nucleus 5	ACE	69	6 years
P06	F	Cochlear Nucleus 5	ACE	47	3 years
P08	F	Cochlear Freedom	ACE	36	13 years
P09	M	Cochlear 3G	ACE	77	17 years
P10	M	AB Harmony	HiRes 120	38	13.5 years
P11	F	AB Harmony	HiRes 120	32	4.5 years
P12	M	AB Harmony	HiRes 120	67	5 years
P13	F	AB Harmony	HiRes 120	38	4 years
P14	F	MED-El Opus	FSP	35	2 years
P15	F	AB Harmony	HiRes 120	39	5 years
P16	F	MED-EL Opus	FSP	61	3 years
P17	F	AB Naida	HiRes 120	34	6 years
P18	F	MED-EL Opus	FSP	69	10 years

2.2.1.3 Procedure

Participants were invited to an appointment at the Ear Institute, and were recruited to take part in take part in the questionnaire validation study and signed a consent form. The questionnaire was printed out and the participant completed it by hand. Participants were advised to skip questions which did not apply to them – for example, a participant who was deaf from birth would skip questions relating to music listening habits before hearing loss.

Validation was carried out in two ways: a CI user review and an expert panel. CI users who filled out the questionnaire were invited to provide comments either verbally or in writing about any aspects of the questionnaire which they felt could be improved. Additionally, a panel of three experts was invited to offer opinions on the quality and suitability of the questionnaire for examining music listening and enjoyment in a wide sample of CI users.

2.2.2 Results and discussion

Feedback from participants completing the Mirza questionnaire, and experts reviewing it, indicated that there were some areas of the questionnaire that they found difficult to complete or confusing**.** It became clear during the testing that some aspects of this particular questionnaire were unsuited to a more varied group of CI users than that available to Mirza et al. (2003). The difficulties presented by the questionnaire which were brought up by the participants and the expert panel are detailed in table 2.2.

The feedback detailed in table 2.2 shows that the Mirza et al. (2003) questionnaire contained a number of issues with wording and formatting, as well as not accounting for participants who might have been deaf pre-lingually or experiences gradual hearing loss. Following this feedback, an amended questionnaire was devised, which is shown in the appendix.

Table 2.2: Issues identified in the questionnaire devised by Mirza et al. (2003) by CI users and expert panel, and the changes made to the final questionnaire.

Issue	**Comments**	**Example**	**Identified by**	**Resulting change**
Wording concerns	Confusing or misleading wording of multiple choice questions	Question 25 is “Compared to before going deaf how is singing now?”, with options being: *1. Just the same, 2. Not quite as good, 3. Not as good, 4. Not very good, or 5. Can’t appreciate it at all:* No options for positive response giving a negative bias	Expert review	Question reworded to make the answer choices clearer and allow for a range of positive and negative reports. New options were: Much worse, Not quite as good, Just the same, A bit better, Much better
Formatting	Little obvious categorisation into subject areas	The questionnaire runs from question 1 to question 27 with no division into subject areas.	Expert review	The revised questionnaire was divided into distinct, well-defined categories.
Formatting	Lack of clarity in grading from 0 to 10	Several questions asked the participant to give a rating on a scale from 0 to 10, but with only five word cues to indicate what the 10 numbers signified.	Expert review	To increase clarity, the rating was changed to a 1 to 5 scale, to match the word cues.
No accounting for pre-lingual deafness	Mirza et al.’s (2003) questionnaire was designed for post-lingually deafened adults undergoing CI surgery	Many CI users were forced to skip the first three questions as they were not relevant to them.	CI user review	Questions were included which related to several possible stages of music listening: before going deaf (where appropriate), during deafness, and post-implantation
No accounting for gradual hearing loss	Mirza et al.’s (2003) questionnaire only took into account the CI user’s experience of music after hearing loss had occurred	Questions asked the CI user to identify their behaviour either before or after their implant, but some CI users noted that there was a difference between their music listening habits when they had normal hearing, to when their hearing loss was partial or complete.	CI user review	Two separate sections were included, one asking about music habits whilst having normal hearing (if applicable), and one asking about music habits when hearing loss was at its worst prior to implantation.

In terms of the results provided by the initial respondents to the Mirza et al. (2003) questionnaire, there is a generally positive view of music listening with a CI when compared to the results of the Mirza et al. study. In that study, less than half of the respondents listened to music after implantation, compared to 70% who filled out the questionnaire as part of this questionnaire validation. Also, the present study's participants averaged a post-implantation music enjoyment score of 7.1 out of ten, which compares very favourably with Mirza et al.'s (2003) participants who scored an average of 2.6 out of 10. While there may be many factors contributing to these differences, such as number of participants, it is interesting to speculate whether improvements in CI technology that have occurred in the decade since Mirza et al.'s (2003) study contributed to the more favourable reports from CI users in the present study.

All apart from three participants (who were deaf from birth) reported listening to music prior to going deaf, nine of these often or very often. Two participants who listened to music prior to deafness no longer listen to music with the implant. Seven participants (44%) reported listening to music post-implantation often or very often. There was a slight decrease between the average scores awarded for music enjoyment before (7.9) and post (7.1) implantation, though half of the participants state that listening to music now is not as good as before going deaf. 37.5% would have had an implant just to listen to music. Six participants played a musical instrument before going deaf, though only one carried on the practice with their implant (playing the piano). Three sang prior to going deaf, and continued to do so with their implant, in choir or church settings.

A new questionnaire was devised following the identification of problems with the Mirza et al. (2003) questionnaire as detailed in table 2.2. The main modifications in the revised questionnaire were in a more structured layout of questions, and changes to response categories to improve clarity and to be appropriate for both pre- and post-lingually deaf adults. The revised questionnaire totalled 40 questions. The first page comprised 6 questions relating to music listening habits prior to deafness. Respondents who were deaf from birth were advised to move straight on to page 2. The second page, questions 7 to 13, covered music listening between loss of hearing and implantation. Page three, questions 14 to 34, cover music habits with the cochlear implant. The final page, questions 35 to 40, asked a number of demographic questions and questions about duration and aetiology of deafness, model of CI and duration of CI use.

2.3 Revised questionnaire study

There were three key goals of the revised questionnaire study.

1. To compare finding of a present day cohort of CI users against Mirza's original findings, thus bringing the research evidence up to date.
2. To compare results from pre-lingually and post-lingually deafened participants and examine the impact this may have on CI users' enjoyment of music
3. To examine any impact demographic factors have on music appreciation.

2.3.1 Materials and methods

2.3.1.1 Participants

Participants were recruited from several groups:

1. CI users who had registered interest in taking part in experiments at the UCL Ear Institute
2. The National Cochlear Implant Users Association website, with a link at http://www.nciua.org.uk/newsletters/research-topics/.
3. The Cochlear Implant User's Group, circulated via email.
4. The Home Counties Cochlear Implant Group, circulated via email/

In total, 34 adult CI users filled out the online questionnaire. The age range was from 34 to 79 (median 63), with 9 male and 24 female CI users taking part (one participant (P2) declined to answer the demographic questions). Duration of deafness ranged from 5 to 64 years, with a median of 34 years. Table 2.3 shows the gender, age, age at implantation, age at first hearing loss, and CI device of 33 questionnaire responders**.**

Table 2.3: Details of 33 responders, including gender, age, age at receiving their CI, age at loss of hearing, and implant make and model. P2 is omitted as they declined to answer demographic questions.

ID	Gender	Age	Age at receiving CI	Age at first hearing loss	Implant and processor
P1	F	49	44	44	Cochlear Nucleus 5
P3	M	79	60	16	Cochlear Freedom AB Naida
P4	M	68	61	35 to 55	AB Naida
P5	F	34	27	3	AB Naida
P6	F	69	59	5	MED-EL Opus 2
P7	F	61	57	Mid 40s	MED-EL Opus 2
P8	M	39	25	From birth	AB Naida
P9	F	62	58	40s	MED-EL Opus
P10	F	54	44	9 or 10	MED-EL Rondo.
P11	F	37	22	6	Cochlear Nucleus 5
P12	M	68	64	50	MED-EL Opus 2
P13	F	63	56	48	AB Naida
P14	F	35	21	16	MED-EL Opus 2
P15	F	38	35	7	MED-EL Opus 2
P16	F	70	64	60	AB Harmony
P17	M	65	56	48	AB Harmony
P18	M	79	67	65	AB Naida
P19	F	64	55	3	Cochlear Freedom N6
P20	F	40	39	Pre-natal	AB Naida
P21	M	82	74	70	Cochlear Nucleus N6
P22	F	67	55	28 - 54	Cochlear Nucleus CP 810
P23	F	67	61	Early 20s	MED-EL Opus
P24	F	69	64	23	Cochlear C810 and C910
P25	M	53	47	12 or 13 (Tinnitus from age of 6)	Cochlear Nucleus 5 (both ears).
P26	M	55	47	9	AB Naida
P27	F	78	70	69	Med-El Opus 2
P28	F	52	49	Birth	Cochlear Nucleus 5
P29	F	67	65	39	MED-EL Opus 3
P30	F	67	59	Early 30s	AB Harmony
P31	F	67	57	3	Cochlear Nucleus CP810
P32	F	36	32	20 months	MedEl Opus 2
P33	F	50	42	2 months	Cochlear Nucleus 21
P34	F	35	27	Birth	AB Naida

2.3.1.2 Procedure

The revised questionnaire was uploaded to UCL’s online survey website Opinio at https://opinio.ucl.ac.uk/s?s=31226. Participants were invited by email to fill in the questionnaire. Those who had taken part in the pilot or the main study were given the option to leave their name in the final field, in order to match their answers across studies.

2.3.2 Results

2.3.2.1 Listening to music

Participants were asked to indicate how often they listened to music before going deaf (if applicable), during deafness and post-implantation. Results are shown in Figure 2.1. All participants who had previously had some hearing listened to music before going deaf, and 28 listened with their implant (82%).

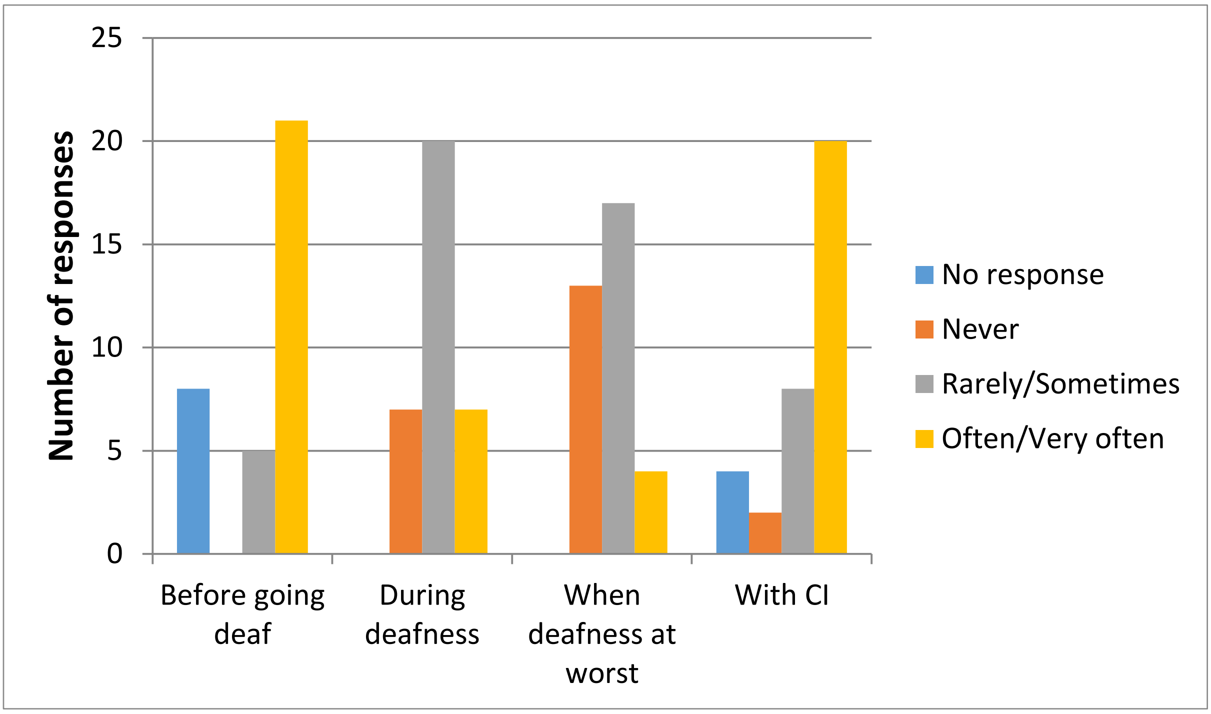


Figure 2.1: Music listening habits responses at different stages of hearing and hearing loss. Those not responding to 'Before going deaf' are those deaf from birth or early childhood and those not responding to the 'With CI' stage do not listen to music with their CI.

Responses to the question regarding type of music listened to in the different stages of hearing and hearing loss are shown in figure 2.2. It is clear the classical and popular music were the most listened to genres at all stages of deafness. Listening to jazz music also interestingly increases with the CI.

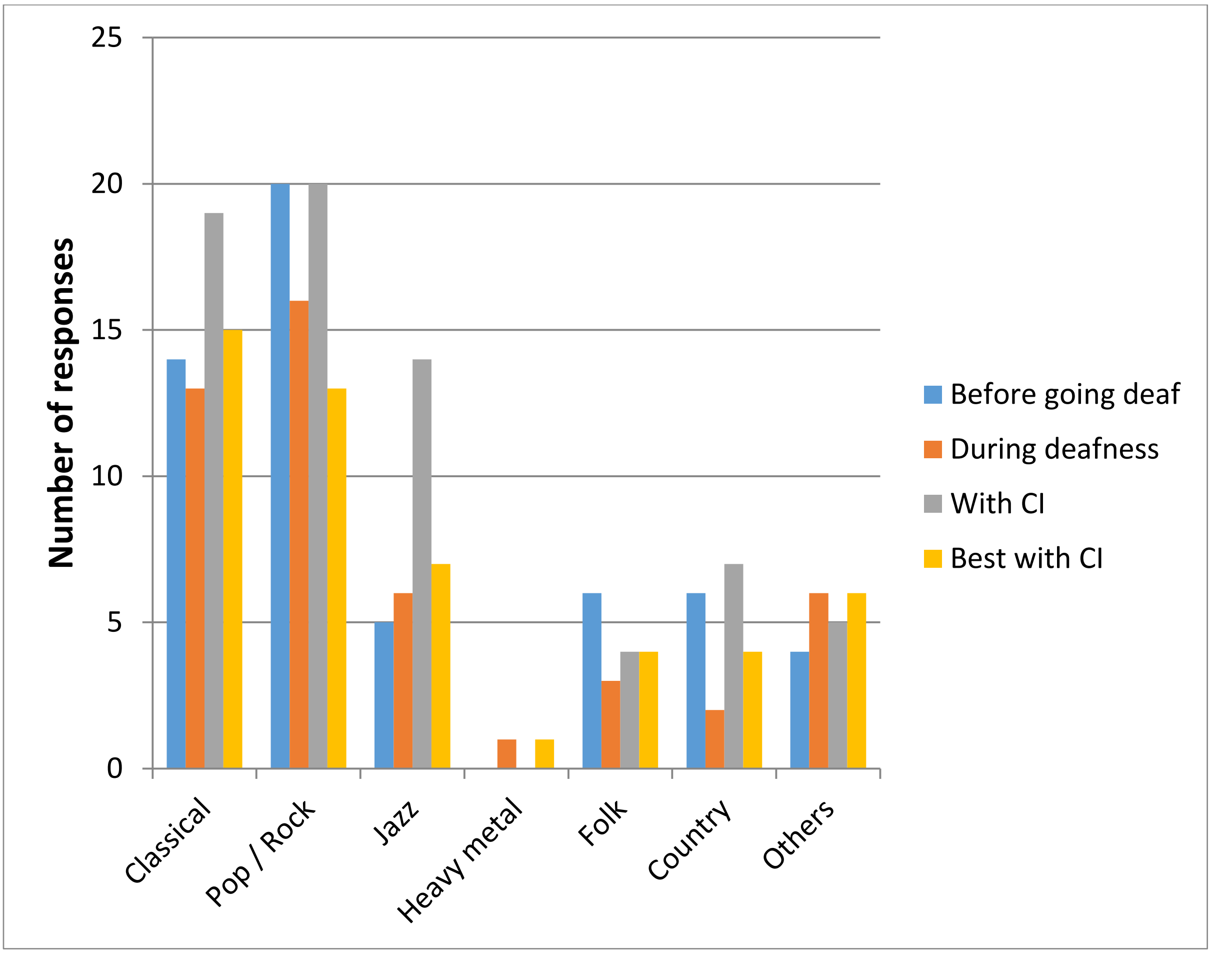


Figure 2.2: Type of music listened to in the different stages of hearing and hearing loss. Responders could choose as many genres as they wished.

Some of the responses given in the “other” section included: Country dance, Church, Hymns, Pop, R & B, Hip-Hop and Soul (before deafness); relaxation tapes, Scottish dance, church, Hymns, and “anything” (during deafness); dance and church, pop, R&B and hip hop (with implant).

Participants also rated their enjoyment of music at the different stages of hearing and hearing loss. Results of this question are shown in figure 2.3. Figure 2.4 shows answers to the question, “Compared to before going deaf, how is listening to music now?” Those reporting enjoying music “Much” or “Very Much” dropped from 20 before going deaf (77% of the 26 who had some hearing initially) to 7 during deafness (21% of all responders), and rose again to 18 with CI (53% of all responders). 63% responded that music was worse with their CI than before going deaf. There was a significant correlation between enjoyment of music and time spent listening to music (rho = 0.91, p < 0.001).

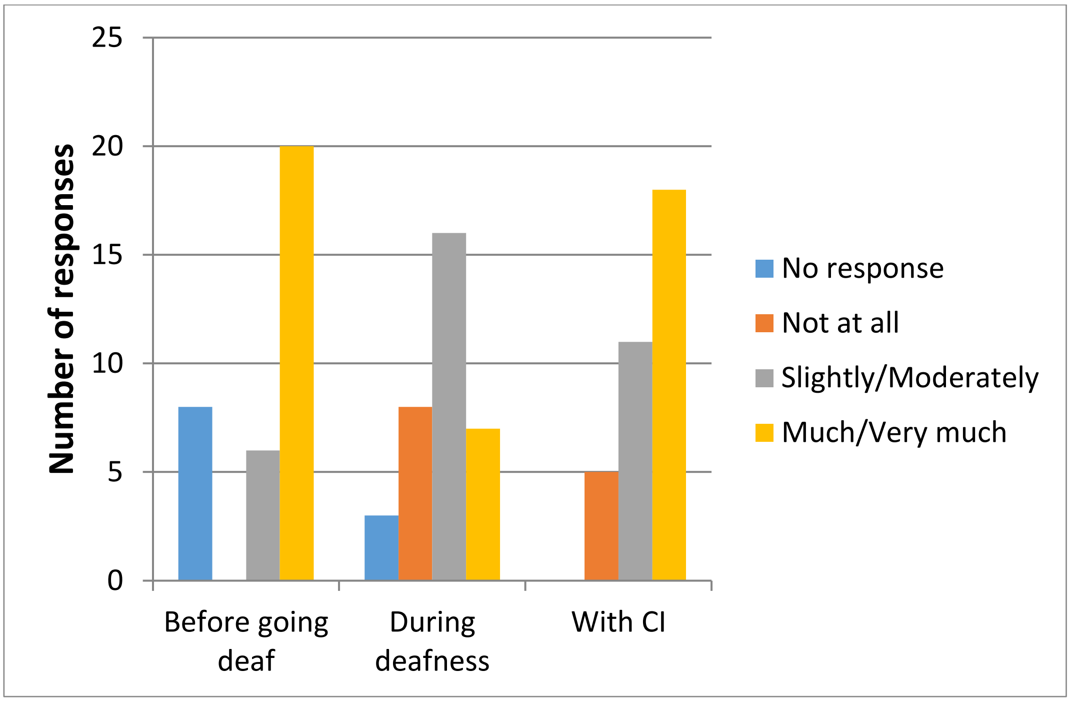


Figure 2.3: Bar chart showing enjoyment of listening to music in the different stages of hearing and hearing loss.

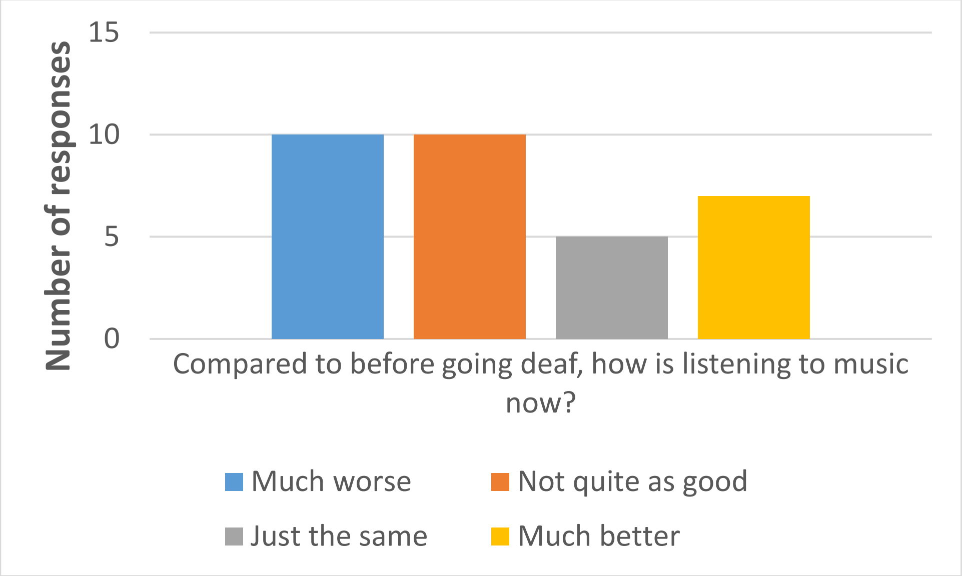


Figure 2.4: Bar chart showing number of individuals responding in each response category.

Comments from participants revealed that many had to rely on memory of music or lyrics in order to recognise or enjoy a song, and the results were still often disappointing, as one commenter pointed out:

> “I just hear noise rather than music. If I recognise a piece by its lyrics or rhythm, it sounds very flat.”

One participant noted that it was “pointless listening to anything new, because I can't hear the tune or harmony.” For another participant, it was impossible to distinguish between voices and instruments.

A number of comments described a smaller, narrower tonal range to the music with the CI. Simpler arrangements were preferred, as one CI user commented:

> “some more complex sounds big orchestra etc difficult especially church organs!”

For others, listening to music with their implant had very few redeeming features, being effortful and not suitable as the leisure activity they enjoyed prior to hearing loss. One participant commented:

> “Have to make more of an effort. Somehow it seems a bit bland and artificial. I don't have in on as general background which I always would have done before.”

However, for one participant, the ability to hear high frequencies, which they had missed whilst using hearing aids, had a positive effect:

> “I could hear high frequencies such as violin, flute, women singing for the first time. I listened to Queen most of my hearing aids life and now able to hear Brian May's solo which was silent back then.”

Overall, respondents described a music listening experience which was disappointing and required effort, with many relying on the memory of music prior to hearing loss.

2.3.2.2 Other musical activities

Participants were asked whether they played a musical instrument or sung during the different stages of hearing and hearing loss. Responses are show in Figure

2.5. 32% played an instrument and 29% sang before going deaf, which dropped during deafness to 21% and 24% respectively, and reached a low of 13% and 21% respectively with CI.

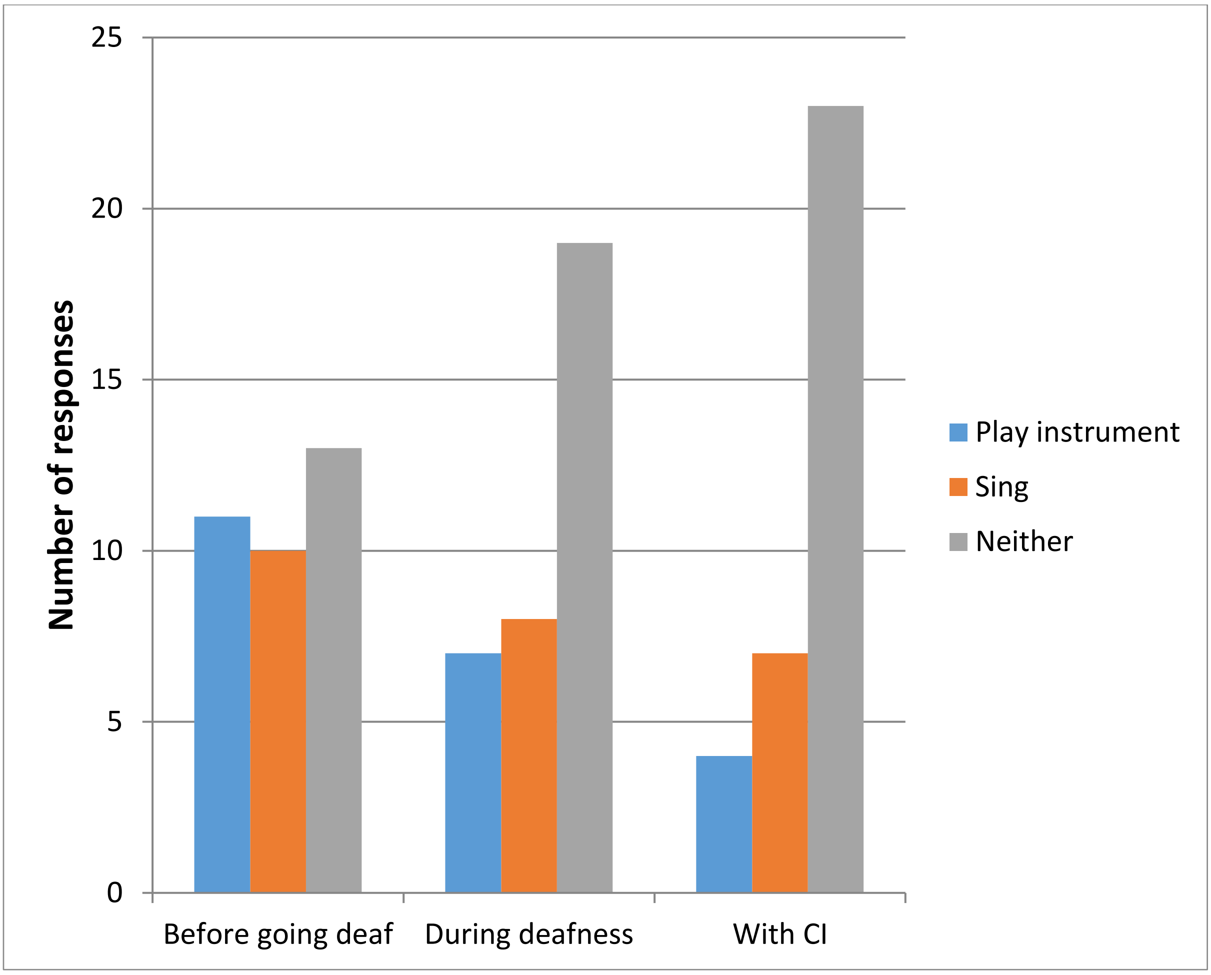


Figure 2.5: Singing and musical instrument playing in different stages of hearing and hearing loss.

Comments from players and singers revealed varying levels of dissatisfaction with the sound of musical instruments with their implants. Different instruments elicited different responses, with one participant reporting:

> “Songs I know played on piano and guitar sound okay to me, but the flute seems to just scream.”

One respondent who played piano and church organ and reported that this was very important had a mixed experience with their implant, giving the following comment:

> “Harder to hear wrong notes played by pedals on the organ. Pitch discrimination isn't as good, but the overall effect is much better.”

The pedals on the organ are usually playing at the lowest frequency of any given piece. The same participant commented with regards to listening to music:

> “Before CI, I couldn't make out treble notes very well, and bass notes were easiest to hear. After CI, it's the other way around!”

This would suggest that the loss of low-frequency hearing (which can be available to HI listeners who use a hearing aid) has had a substantial impact on this participant’s experience of listening to and playing music.

Another participant who made the following comment regarding their own piano playing reported a more negative experience:

> “I try to get back to the piano, but I drown in sound and need to play as quietly as possible.”

The same participant described their experience of playing a piano with their implant as “Disappointing and off-putting.”

For others, exploring singing or a musical instrument was used as a way to appreciate music better with their implant, even if they didn’t play before. One participant commented:

> “I am trying to play my son's keyboard to try to teach myself to hear musical notes but at present cannot recognise them.”

Another participant played saxophone and clarinet as well as taking singing lessons, but had played a different instrument prior to their CI (they did not state which instrument). These two were the only participants who expressed an interest in new music practice which they had not had prior to their CI.

2.3.2.3 Music enjoyment by device

Of the 34 questionnaire respondents, 33 indicated the manufacturer of their device. Figure 2.6 shows the reported enjoyment of music with a CI for participants using different devices. For MED-EL and Cochlear users, a comparison between those who get a moderate amount of enjoyment of music and those who enjoy music a lot shows very similar numbers. In contrast, the majority of AB users report enjoying music much or very much.

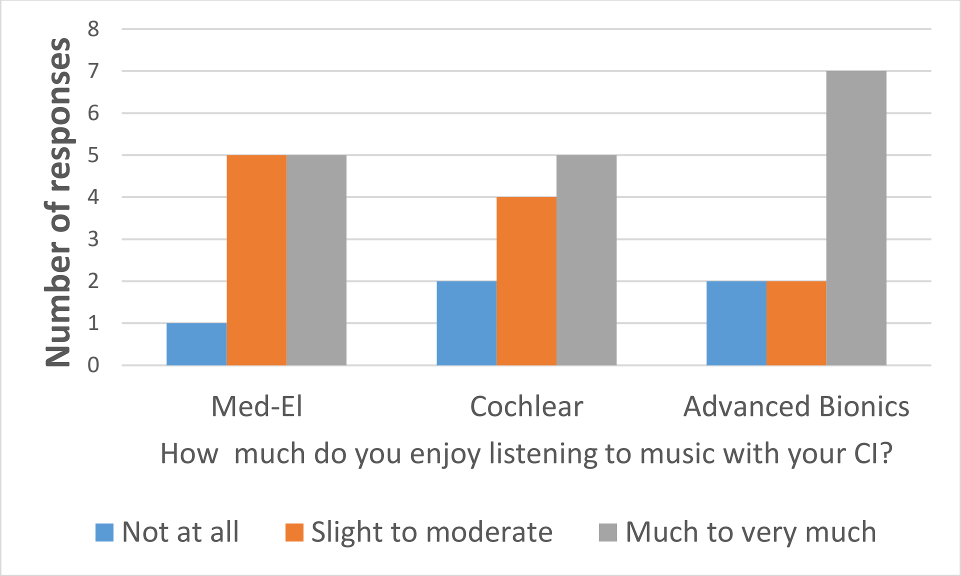


Figure 2.6: Enjoyment of music by device

2.3.2.4 Time taken to listen to music after implantation

It took an average of 30 weeks for CI users to start listening to music post-implant, though many stated that they started listening immediately or within a month. For some, the choice to listen to music was not their own but dictated by others:

> "I was having to try to cope with music from very early on as my children were learning songs and instruments and also wanted to listen to music at home."

For another respondent, the choice of musical genre to listen to was dictated by the limitations of the implant:

> "Straight away but had to start with classical music to identify each instruments as speeches were like robotics at the time"

Some participants encountered music soon after their implantation due to social activities, such as going to church, with one commenter saying they “listened because it is part of what is going on but not enjoyed”. Another whose early CI music experience occurred listening to hymns at church remarked that they “still find it difficult to identify any songs that are being played.”

For others, the experience was more positive, with one respondent reporting that they started listening to music two days after switch on, and that they were “astonished to find I could recognise TV show theme music (Dr Who and All Creatures Great and Small) so early on.”

For most participants, it took time after implantation before they were able to enjoy music, with six responders stating that they still are not able to appreciate music or that it is still an ongoing process. One remarked: “I have been implanted 5 years and have no appreciation of music”, and other that they “still struggle with anything with complex harmonies”.

One participant noted that music sounded completely different to how they remembered and wondered if the problem was with their hearing or their memory. Of the 20 participants who gave a specific amount of time it took for music to become enjoyable, the average length of time was 1 year and 3 months (median 6 months), with a range of no time (music was enjoyable immediately) and 8 years.

2.3.2.5 Demographic factors

2.3.2.5.1 Gender

An independent samples t-test was run to compare frequency of listening to music and enjoyment of music between male and female respondents. No significant difference was shown on scores for frequency of listening to music ($t(31) = -0.7$, $p = 0.49$) and for enjoyment of music ($t(31) = -0.66$, $p = 0.51$) based on the gender of the respondent.

2.3.2.5.2 Age at hearing loss

Demographic data in this study were not normally distributed. Therefore correlations were obtained using Spearman’s rank correlation. There was a significant negative correlation between age at hearing loss and enjoyment of music (rho = -0.38, $p = 0.03$) but no significant correlation between age at hearing loss and frequency of listening to music (rho = -0.29, $p = 0.1$). Figure 2.7 shows the percentage of pre-lingually deafened and post-lingually deafened respondents who responded to the question “How much do you enjoy music?” For the purposes of this question, pre-lingual deafness was defined as hearing loss occurring at or before the age of six years. Additionally, none of the pre-lingually deafened respondents were implanted with a CI before the age of 18 (the respondent with the earliest age at implant surgery was implanted at the age of 21). This figure shows that more that 80% of pre-lingually deaf participants report enjoying listening to music much or very much, compared to less than 40%

of post-lingually deafened respondents. Additionally, none of the pre-lingually deaf respondents stated that they got no enjoyment from music at all.

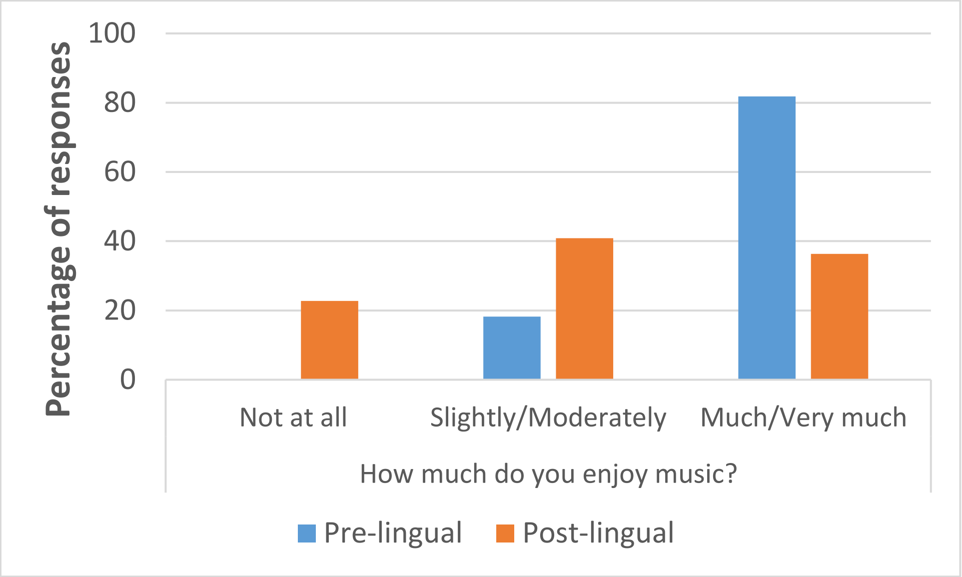


Figure 2.7. Bar chart showing the percentage of respondents who reported how much they enjoyed listening to music: not at all, slightly/moderately or much/very much, separated into the pre-lingually and post-lingually deafened participants.

2.3.2.5.3 Age at receiving CI

There was no significant correlation between age at implant surgery and enjoyment of music (rho = -0.31, p = 0.08). However, there was a significant negative correlation between age at implant surgery and frequency of listening to music (rho = -0.37, p = 0.03). Figure 2.8 shows that 100% of respondents who received their CI before the age of 40 report listening to music often or very often, compared to 33% of those implanted between the ages of 40 and 49, 56 % of those implanted between the ages of 50 and 59, and 40% of those implanted over the age of 60.

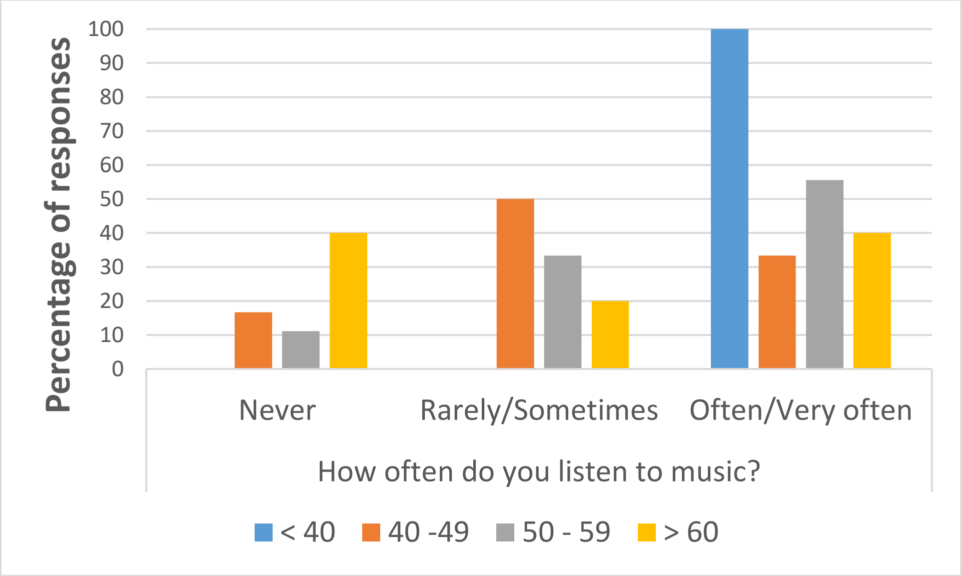


Figure 2.8. Bar chart showing the percentage of respondents reporting their frequency of listening to music: never, rarely/sometimes, or often/very often, separated by their age at receiving implant.

2.3.2.5.4 Duration of deafness

There were no significant correlations between duration of deafness and enjoyment of music (rho = 0.22, p = 0.21) or time spent listening to music (rho = 0.44, p = 0.81).

2.4 Discussion

In the research described in this chapter, the questionnaire by Mirza et al. (2003) was piloted, amended and expanded to be useful for gaining insight into the music listening experience and enjoyment of CI users from a wide range of backgrounds. Mirza et al. (2003) observed that at the time of their study, there was a relative scarcity of research into music appreciation in CI users, compared to that devoted to speech perception and understanding. Over a decade later, there has been some redress of this imbalance, with many researchers devoting considerable effort towards attaining a greater understanding of the musical experience of CI users. However, none of these studies have looked at the differences between pre- and post-lingually deafened CI users in their experience of music. Music remains a topic of great concern and interest for a large number of CI users, who express a desire for improvement in their ability to appreciate and enjoy music.

Results of the revised questionnaire are generally more positive than in Mirza et al.’s (2003) study. It is possible that technological advances in the thirteen years since that study was published have allowed CI users a greater appreciation of music. However, there are other questionnaire studies carried out more recently than Mirza et al.’s 2003 questionnaire, in which results are less positive. In the present study, 59% of respondents reported listening to music often or very often. Other studies carried out in the last seven years have had less favourable reports, with for example, only 38% of participants in one study listening to music more than two hours a week (Lassaletta et al., 2008), or 32% of another study’s participants listening to music often or always (Fredrigue-Lopes et al., 2015). It is also important to note that many of the people answering the present questionnaire had been recruited to take part in a study relating to music listening with a CI, and therefore were more likely to be keen music listeners who will make an effort to improve their music listening experience in any ways they can.

Another explanation for the generally more positive report of music listening and enjoyment given by respondents to the present questionnaire can be found by examining demographic factors. In the study by Mirza et al. (2003), all participants were post-lingually deafened, whereas the present study includes both pre- and post-lingually deafened participants. Pre-lingually deafened patients were much more likely to report enjoying listening to music much or very much. This may be a consequence of post-lingually deaf adults comparing their experience of music with the CI negatively with their previous NH music listening experience. In contrast to this, pre-lingually deaf respondents will not have a prior experience of music with which to compare their CI music listening experience. This is supported by the fact that children with CIs, who also have no memory of music with normal hearing, are much more likely to report enjoyment of music than adults with CIs (Nakata et al., 2005; Hopyan et al., 2011).

Duration of implant use was not found to be correlated to enjoyment of music, which concurs with results found in previous studies (Gfeller et al., 2000, Lassaletta et al., 2008). However, age at receiving the implant did correlate with frequency of listening to music, with all respondents who were implanted below the age of 40 reporting that they listened to music often or very often. A similar result was seen in the original study by Mirza et al. (2003), who divided their respondents into ‘Listening’ and ‘Non-listening’ groups. Those who listened to music had an average age at implantation of 42, compared to 54 for those who did not listen. A possible explanation for this finding is that those implanted under the age of 40 were able to experience music during the ages when typically interest in music is stronger, and perhaps there is more time to listen to music, before responsibilities such as work and family take up more time. There was also a significant correlation between time spent listening to music and enjoyment of music, which has also been found in previous studies (Gfeller et al., 2000). In the present study, as with the 2000 study, it is not clear whether more time spent listening to music led to greater enjoyment, or that those who already enjoyed music more spent more time listening to it. However, given that those implanted under the age of 40 spent the most time listening to music, it could be that another crucial element in the relationship between time spent listening to music, and the enjoyment of it, is gaining the ability to listen to music at an age when the interest is strong enough to persevere with the activity even if it may initially be a less than satisfactory experience.

Looking at the relationship between device used and enjoyment of music, participants with AB devices were more likely to report enjoying music much to very much, compared to users of MED-EL or Cochlear devices. While this may be related to the availability of virtual pitches in the HiRes 120 strategy available to AB users, it is difficult to make any conclusions based upon the present study due to the small number of participants, as well as confounding factors such as age at onset of deafness or at implantation.

Despite the overall results which were more positive than in many previous studies, 62.5% of responders described listening to music as either much worse or not quite as good as they remembered before going deaf. Add to this the fact that less than half of the responders who played an instrument before going deaf carried on with this activity with their CI, it is clear that the experience of listening to music and participating in musical activities is particularly disappointing to those with a memory of their experiences prior to hearing loss.

Comments from responders show that many CI users find listening to music a disappointing experience, which takes effort and provides limited rewards. Some commentators said that melody and harmony were difficult to distinguish, with an overall effect described as overwhelming. This suggests that the CI is not able to effectively separate the different aspects of music such as melody and harmony, creating a listening experience without many of the subtleties and complexities intended by the composer or artist. This is probably due to the lack of fine structure information provided by the implant (Zeng, 2002), which is important for such aspects of music as pitch perception, cuing place of articulation, voicing and tone quality (Rosen, 1992, Schauwers et al., 2012). This lack of fine structure information also means that timbre recognition was difficult, with some reporting that distinguishing between instruments or even between a voice and an instrument was difficult.

Half of the responders described their level of enjoyment of music as moderate or less. There is clearly still a need for developments in CI technologies which will improve the experience of music for CI users, particularly in their ability to perceive pitch.

2.5 Limitations of the study

There are a number of ways in which the questionnaire could have been strengthened. Jackson (2000) recommends that one of two processes should be followed in the design stage for questionnaires which include qualitative data such as opinions and personal reflections, as the present questionnaire does. In one process, members of the target group should be invited to go through the survey questions and express verbally their thought processes as they answer the questions, to ensure that the questions are not being misinterpreted.

Alternatively, small group discussions with members of the target group should be carried out. With the study described in this chapter, a version of the first process was carried out, as the researcher was present with the participants as they filled out the Mirza et al. (2003) questionnaire, and was able to have discussions with the participants regarding any questions they were uncertain about. However, this was not done with the specific aim of eliminating misconceptions, so some of these may have been overlooked.

Jackson (2000) also recommends that, once a pool of items has been collated, the survey should be administered to a group of people similar to the target group of the survey, to give feedback. It is advised that the questionnaire should be administered to a sample of sufficient size to allow an exploratory factor analysis, with at least 100 being the recommended number of participants (Rattray & Jones, 2005). However, that would have been difficult in this case with the time and resource limitations, as well as the small proportion of the general population who use CIs.

Likert type scales operate on the idea that there is a continuous spectrum of experience that can be placed at a point upon a scale. Scales with an odd number of options, as used in this questionnaire, allow for a neutral midpoint. It has been argued that this neutral options should be removed, forcing the respondent to choose a side; however this could be disagreeable to participants who genuinely feel neutral towards the issue at hand, and make them disinclined to continue with the survey (Burns & Grove 1997).

For future studies using the questionnaire devised here, it would be prudent to carry out some of the recommendations mentioned above, including carrying out the “think aloud” or small group discussion processes for qualitative questions, and administering the questionnaire to sufficient participants to allow for a factor analysis. In this way the questionnaire can be further strengthened to endure that it is producing valid and reliable data.

2.6 Summary of findings

1. The CI users who responded to the questionnaire spent more time listening to music, and reported greater enjoyment, than those responding in 2003 to Mirza et al.’s study. This may be due to changes in candidacy factors such as greater residual hearing, improvements in CI technology, or to a bias amongst this particular group of participants to be particularly interested in improving their music listening experience.

2. Pre-lingually deafened participants are more likely to report that they enjoy listening to music much or very much, possibly due to their lack of a NH experience of music with which post-lingually deafened adults can compare their CI music listening experience.

3. Respondents who received their CI before the age of 40 all reported listening to music often or very often.

4. Continuing to play a musical instrument is difficult for many CI users, which may be due to impaired timbre perception, which could be improved by training.

5. Music is still disappointing for many CI users, with post-lingually deafened adults reporting that music is not as enjoyable to listen to as before they went deaf.

Chapter 3 – Pitch perception in musical chords for CI users: piloting and developing a test battery

3.1 Introduction

The previous chapter demonstrated the importance of listening to music for CI users and that there is potentially an increase in the number of individuals reporting that they enjoy music. In previous studies, perception of music has often been reported as less than satisfactory for CI users (McDermott, 2004) and it is commonly rated the most important aspect of hearing for CI users after speech perception (Stainsby, et al., 1997; Gfeller et al., 2000). Therefore, the generally greater appreciation of music reported by participants of the questionnaire described in chapter 2 suggests a positive improvement which should be built upon. While CIs can accurately deliver gross rhythmical aspects of music, the reduced spectral information available and lack of delivery of rapid temporal fluctuations hinders perception of pitch-related aspects of music such as musical timbre, melody and polyphony (McDermott, 2004; Zeng et al., 2008).

There have been a growing number of studies looking at CI users' abilities to perceive and appreciate various aspects of music, including rhythm, melody and timbre (McDermott, 2004; Looi, et al., 2012). CI users' perception of musical pitches in isolation and in melodic sequences has been widely studied (Fujito and Ito, 1999; Gfeller et al., 2002; McDermott, 2004; Pressnitzer et al., 2005; Galvin et al., 2007; Looi et al., 2008). One area that has received relatively little attention in CI users is the perception of musical chords (Vongpaisal et al, 2006, Boeckmann-Barthel et al., 2013). Chords are a frequent component of Western music, with some of the most commonly occurring being major, minor and augmented chords. As musical chord perception is based upon perceiving notes presented with specific interval relationships between the component notes, accurate perception of pitch is crucial to the perception and enjoyment of musical chords.

Previous studies have shown that while aspects of music such as tempo and rhythm are relatively well preserved, the perception of pitch is much more difficult for CI users. The spectral location (or place) information is the most apparent pitch cue for a CI user because much of the temporal pitch detail (rapid fluctuations in stimulus) is not conveyed for frequencies above 200 to 300 Hz due to the processing approach used within CIs (Zeng et al., 2008). This affects melody and voice pitch perception. In CI processing, only the temporal envelope is delivered, and the faster temporal fluctuations above about 300Hz are discarded. These are extracted in different frequency bands and each of these sends information to an individual channel in the CI with the intention of stimulating a specific neural population. The information in each frequency band is used to modulate the amplitude of a biphasic electrical pulse train delivering information for a specific channel. The primary purpose of this signal delivery approach has been to provide speech understanding through the delivery of the slow envelope fluctuations in the acoustic signal, which are known to be important for speech understanding (Smith et al., 2002).

Many studies have demonstrated that CI users have greater difficulty with pitch perception compared to NH listeners. CI users often need to use cues other than pitch, such as lyrics or rhythm, in order to recognize familiar melodies (Schulz and Kerber, 1994; Gfeller et al., 2002; Kong et al., 2004). Detecting differences in pitch is much more difficult for CI users. In a pitch ranking task performed both by CI users and NH listeners, it was shown that while the mean difference limen for NH participants was 1.13 semitones, CI users averaged a 7.56 semitone difference limen, and performance amongst the participants with CIs varied greatly, with individual difference limens between one and 24 semitones (Gfeller et al., 2002). A later study which compared the abilities of CI and NH listeners to rank the pitches of sung vowels found that CI users performed at chance when asked to rank a one semitone difference (Sucher & McDermott, 2007). Identifying musical patterns also becomes more difficult when the differences between the tones that comprise the pattern decrease from five semitones to one (Galvin et al., 2007).

CI users also have difficulty in identifying an altered note in a repeated melodic sequence (Pressnitzer et al., 2005). In an experiment with NH and CI participants, each participant’s pitch ranking ability was first assessed, revealing that the CI users could pitch rank at differences between 2 and 7 semitones, whereas the NH control group could pitch rank down to 0.2 of a semitone. In the experimental task, a four note chromatic melody comprised of bandpass-filtered complex tones was presented twice, with one note changing in the second presentation. Identifying the changing note proved impossible for most CI users, even when the interval between the changing notes was larger than each individual listener’s pitch ranking threshold. The NH group scored near to the ceiling limit of the test.

The few studies looking at pitch perception in the context of musical chords have tested CI users’ abilities to assess whether two chords presented one after the other are the same or different. In the study by Vongpaisal et al. (2006), eight CI listeners aged between 6 to 19 years, and 13 NH 5 year olds took part. They were presented with two sequences for comparison, each starting from the note known as middle C or C4, with a frequency of 262 Hz. The C major triad (presented sequentially as an ascending and descending arpeggio C4-E4-G4-E4-C4) was either presented twice, or alongside C minor (C4-E♭4-G4-E♭4-C4) or C augmented (C4-E4-G♯4-E4-C4). In each comparison, the possible difference between sequences amounted to just one semitone. There was a significant difference between the two groups in their ability to judge whether the two sequences were the same or different, with the NH children performing well above chance, whereas the CI users were at or below chance level on all comparisons.

The notes in musical chords are typically presented simultaneously and not sequentially as in the Vongpaisal et al. (2006) study, but only a handful of studies have looked at the perception of simultaneously presented tones with CI users. A number of studies have tested CI users abilities to listen to multiple concurrent tones and identify the number of tones present. This is a task that can be difficult for NH listeners, particularly non-musicians, and listeners tend to underestimate the number of tones when three or more are presented (Huron, 1989). In a study by Donnelly et al. (2009), twelve post-lingually deafened adult CI users and twelve NH controls listened to stimuli which consisted of one, two or three simultaneous tones (either pure tones or piano tones, presented acoustically). The NH group performed significantly better at identifying whether a stimulus contained multiple components; though were more likely to identify three pitch stimuli as two pitches. The CI group performed close to chance levels for the identification of two and three component stimuli, often reporting that they perceived one pitch component.

It is clearly very difficult for CI users to perceive that a sound contains multiple simultaneous pitches when presented acoustically. With direct electrode stimulation to a specific sub-set of electrodes, however, results can be better. One study involved experiments similar to Donnelly et al. (2009) using direct electrical stimulation (Penninger et al., 2013). Stimuli consisted of biphasic pulse trains of two different kinds. The first kind was stimuli made up of one modulation frequency, which were applied to either a basal, middle, or apical electrode. The second kind was made up of two modulation frequencies, which were applied either both on an apical electrode, or one on an apical and one on a middle or basal electrode. Contrary to the previous study by Donnelly et al. (2009), participants were significantly above chance at identifying the number of tones in the stimulus. However, when two frequencies were applied to a single rather than two electrodes, performance fell from over 80% correct to just above chance level. Similar results were attained in a further study which added stimuli consisting of three simultaneous pitches (Penninger et al., 2014). In this study, performance on the task improved as the distance between electrodes and the difference between the modulation frequencies increased.

Other studies have looked at the perception of simultaneously presented tones specifically in the context of musical chords, using the MuSIC (musical sounds in cochlear implants) test battery. This test was devised by the CI company MED-EL to facilitate assessment of CI user’s musical perception abilities, and includes an adaptive chord discrimination test, in which listeners must discern if two chords, comprised of piano tones, are the same or different. In this test, the chords may be comprised of anything from two to seven tones, with only one of the tones changing. Stimuli progressed to the next level of difficulty after three correct answers. The pitch difference between the changing note in the two chords ranged in difficulty from two octaves down to a single semitone. Using this test, Brockmeier et al. (2011) found that CI listeners performed significantly worse that NH listeners, with an average score across all difficulty levels of 73.7% compared to NH 86.6%. Boeckmann-Barthel et al. (2013) also carried out this task, and found that CI listeners were significantly better at identifying the change in chords if the notes fell in frequencies above middle C (262 Hz). NH listeners performed equally well regardless of the pitch of the notes, and all participants performed above chance on the task.

The present study aims to address the limitations of the current literature looking at the perception of musical chords in CI users. By expanding on the approaches of the studies of Vongpaisal et al. (2006) and Boeckmann-Barthel et al. (2013), a number of parameters were chosen in order to examine difference facets of pitch perception in a musical context. These parameters are described below.

Parameter 1: Presentation of chords: Vongpaisal et al. (2006) looked at sequentially presented chords, and Boeckmann-Barthel et al. (2013) studied simultaneously presented chords; this study compares simultaneous and sequential presentation of musical chords in the same CI users.

Parameter 2: Chord contrast: To provide comparison with Vongpaisal et al.'s (2006), the same chord contrasts of major-minor and major-augmented were used.

Parameter 3: Chord root: Boeckmann-Barthel et al. (2013) found that detecting differences between chords was easier for CI users at frequencies above 262 Hz (C4), which was the frequency of the lowest note of the chords used by Vongpaisal et al. (2006). The present study covered chord root frequencies spanning the range of both of these studies. There is some evidence that higher frequencies may be easier than lower frequencies for CI users in pitch perception tasks using pure tones (Smith et al., 2009). By varying the roots of the chords across two octaves (C4, G4, C5 or G5), it was possible examine users' pitch perception across a number of spectral ranges, to give an indication if there is a particular frequency range in which it is easier for CI users to detect pitch changes.

Parameter 4: Octave span: Due to the nature of CI sound processing strategies, which split the input signal into a number of frequency bands, it can be difficult for CI users to distinguish different pitches within the same band (Zeng, 2004). Additionally, in most current day sound processing strategies, electrodes within the cochlea are stimulated in a monopolar coupling configuration (Srinivasan et al., 2013), which can cause large current spread across the cochlea, which can have the effect of stimulating a larger population of neurons than is ideal, and adjacent electrodes may stimulate the same groups of neurons (Townshend et al., 1987). In order to counteract the effect of these aspects of CIs, the Octave

Span parameter was included. Chord discrimination was tested in three conditions, with the notes of the chord spanning one, two or three octaves.

In addition to the parameters mentioned above, a vowel-consonant-vowel (VCV) test was included in the pilot test battery as a basic measure of speech perception, to examine any possible correlations between pitch and speech perception in the participants. The VCV test is widely used in tests of speech and language perception, as it allows analysis of perception of consonants both with and without visual cues, and it is easily adaptable for different languages. It is commonly used as a basic test of speech perception in studies with CI users (Rosen et al.,1999; Dorman et al., 1997; Vickers et al., 2001). Components of spectral pitch such as fundamental frequency are important for aspects of speech perception such as stress and intonation, and speech in noise (Lin et al., 2009). Recognition of consonants relies on spectral shape and slow temporal envelope cues rather than pitch information, in order to discern distinct consonant features such as the manner and place of articulation (Faulkner 2006; Donaldson & Kreft 2006). However, identifying the place of articulation may be impaired due to the limited spectral information supplied by the CI (Verschuur, 2009), which also has an impact on the perception of pitch and speech in noise. Therefore this study includes a consonant recognition test, in order to make a preliminary assessment of connections between pitch and speech perception abilities.

With the aim of defining characteristics important to include in a chord discrimination test, the following questions were examined:

1. Is it easier to detect a change in a musical chord when the notes are presented simultaneously or sequentially?

2. Is it easier to detect a change in musical chords when the middle note falls (Major-Minor) or the top note rises (Major-Augmented) in pitch?
3. Are there specific spectral regions in which it is easier to detect frequency changes?
4. Is there a difference in ease of detection when the components of the chord all fall within the same octave or when they fall across two or three different octaves?
5. What is the relationship between pitch perception in musical chords and results on the VCV test?

3.2 Materials and Methods

Ethics approval was given by the UCL ethics committee (UCL Ethics Project ID Number: 3523/001) prior to data collection for this study.

3.2.1 Participants

Participants were recruited from a group of CI users who had registered interest in taking part in experiments at the UCL Ear Institute, and whose details were available on a confidential participant database. Eighteen adults CI users took part, comprising six participants for each device manufacturer (Cochlear, MED-EL and Advanced Bionics (AB)). Table 3.1 details the variety of devices used for each participant. These participants were paid £15 for their participation, and their travel expenses were reimbursed. There were 5 male and 13 female participants, ranging in age from 32 to 77 (median age 56.5).

Table 3.1: Device, sound processing strategy, age and duration of CI use of 18 participants. Information that was not provided by the participant is marked U. FSP refers to Fine Structure Processing and ACE to Advanced Combination Encoder.

Participant	Gender	Device	Sound processing strategy	Age	Duration of CI use
P01	M	MED-EL Duet	FSP	61	5 years
P02	F	Cochlear Freedom	ACE	69	5 years
P03	F	MED-EL Opus 2	FSP	60	2 years
P04	F	Cochlear Nucleus 5	ACE	53	2 years
P05	F	Cochlear Nucleus 5	ACE	69	6 years
P06	F	Cochlear Nucleus 5	ACE	47	3 years
P07	M	MED-EL Opus 2	FSP	66	2 years
P08	F	Cochlear Freedom	ACE	36	13 years
P09	M	Cochlear 3G	ACE	77	17 years
P10	M	AB Harmony	HiRes 120	38	13.5 years
P11	F	AB Harmony	HiRes 120	32	4.5 years
P12	M	AB Harmony	HiRes 120	67	5 years
P13	F	AB Harmony	HiRes 120	38	4 years
P14	F	MED-El Opus	FSP	35	2 years
P15	F	AB Harmony	HiRes 120	39	5 years
P16	F	MED-EL Opus	FSP	61	3 years
P17	F	AB Naida	HiRes 120	34	6 years
P18	F	MED-EL Opus	FSP	69	10 years

3.2.2 Apparatus

Prior to experimentation headphone frequency response measures were conducted to determine if headphones could be used with the CI sound processor. Measurements were made using a Ono Sokki portable dual channel

FFT analyser. Sennheiser HD600 and Sennheiser HD414 headphones were tested to determine which were the optimal set of headphones to use. Frequency response through speakers was compared to response using the headphones placed over the Cochlear Freedom sound processor and the response measured using a monitoring cable which delivered the output of the sound processor to the spectrum analyser. This output was compared to the original stimulus presented through the headphones and recorded using the Bruel and Kier artificial ear and the spectrum analyser. The headphones were taken off and replaced 3 times and new recordings made to look at the stability of the response. The most stable response with headphone replacements that covered a good frequency range was seen with the HD414 headphones which had flat sponge pads and were not circumaural phones.

The Chord Discrimination test was administered using a script set up for the Apex 2.1 (Unified Version), (Geurts & Wouters, 2000). The script was a modified version of the “Constant Stimuli” module that was available with the software. VCV tests were controlled using MATLAB scripts. Participants were tested in a quiet room. Sound was presented through Sennheiser HD414 headphones connected to a Dell Latitude touch-screen laptop.

3.2.3 Stimuli and procedure

Initially, five participants were tested in order to discern the appropriateness of apparatus and stimuli. During this run the headphones used were of the Sennheiser 2101 model. Following this, the remainder of the pilot study was conducted using Sennheiser HD414 headphones. Each participant attended for one, two or three sessions of approximately 1.5 to 2 hours long each. The same tests (Chord Discrimination Test and VCV test) were repeated at each session.

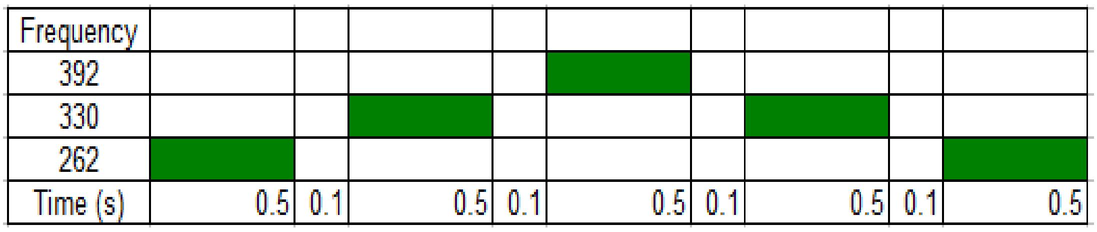
3.2.3.1 Chord Discrimination Test

Stimuli for the Chord Discrimination Test were prepared using CoolEdit 2000. The chords were combinations of sinusoids with a 44.1 kHz sampling frequency, duration of 0.5 seconds and cosine onset offset ramps of 0.1 seconds. Stimuli were calibrated to have the same root mean square (RMS) level. The details of the stimuli are outlined below.

Factor 1: Presentation Mode (Simultaneous, Sequential)

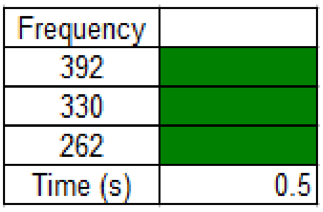
For simultaneous stimuli presentation, three 0.5s pure tones were combined such that all the tones were presented at the same time with the same onset point, thus creating a chord. For sequential stimuli, the same pure tones were concatenated in an ascending then descending order, with 0.1s of silence between each tone, following Vongpaisal et al. (2006). For example, for the C major triad beginning at C4 (262 Hz), the simultaneous stimulus was comprised of C4 (262 Hz), E4 (330 Hz) and G4 (392 Hz) presented at the same time. The sequential stimulus for the same triad was created in the following order: C4-E4-G4-E4-C4 (262-330-392-330-262 Hz). A schematic and notation of the chord stimuli is represented in figure 3.1.

(a)



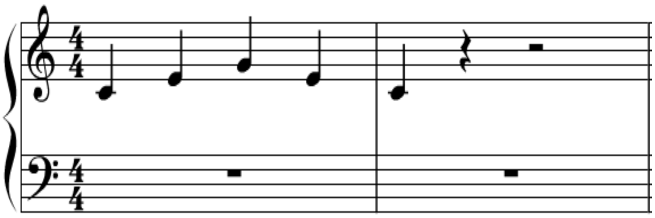
Frequency									
392					🟩				
330			🟩				🟩		
262	🟩								🟩
Time (s)	0.5	0.1	0.5	0.1	0.5	0.1	0.5	0.1	0.5

(b)



Frequency	
392	🟩
330	🟩
262	🟩
Time (s)	0.5

(c)



(d)

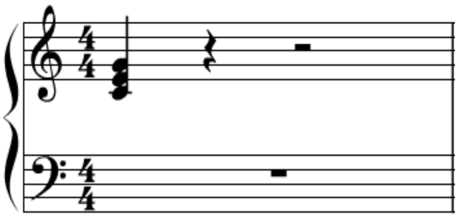


Figure 3.1: Schematic and notation representing the timings of the simultaneous and sequential chord stimuli. Shown here is the C4 one-octave condition. The images represent: (a) Schematic of a sequential stimulus; (b) Schematic of a simultaneous stimulus; (c) Musical notation of a sequential stimulus, and (d) Musical notation of a simultaneous stimulus.

Factor 2: Chord Contrast: (Major-Minor, Major-Augmented)

The standard in each trial was a major chord (Vongpaisal et al., 2006). The odd one out was either a minor chord (in which the middle note dropped by one semitone) or an augmented chord (in which the top note was raised by one semitone).

Factor 3: Chord root: (C4, G4, C5, G5)

The chord root – the lowest component of each chord – was either C4 (262 Hz), G4 (392 Hz), C5 (523 Hz) or G5 (784 Hz).

Factor 4: Octave Span: (One, two, three)

In the one octave span condition, all three notes that comprised the chord came from within one octave. For the two octave condition, the top two notes were in the octave above the chord root. For the three octave condition, the middle note was one octave above the chord root, and the top note was two octaves above the chord root. The exact frequencies used in each stimulus set are shown in Table 3.2.

Table 3.2: List of frequencies of the pure tones in each stimulus set.

Chord root	Octave span	Modality	Notes	Frequencies
C4	1 Octave	Major	C4, E4, G4	262, 330, 392
		Minor	C4, E♭4, G4	262, 311, 392
		Augmented	C4, E4, G♯4	262, 330, 415
	2 Octaves	Major	C4, E5, G5	262, 659, 784
		Minor	C4, E♭5, G5	262, 622, 784
		Augmented	C4, E5, G♯5	262, 659,831
	3 Octaves	Major	C4, E5, G6	262, 659, 1568
		Minor	C4, E♭5, G6	262, 622, 1568
		Augmented	C4, E5, G♯6	262, 659, 1661
G4	1 Octave	Major	G4, B4, D5	392, 494, 587
		Minor	G4, B♭4, D5	392, 466, 587
		Augmented	G4, B4, D♯5	392, 494, 622
	2 Octaves	Major	G4, B5, D6	392, 988, 1175
		Minor	G4, B♭5, D6	392, 932, 1175
		Augmented	G4, B5, D♯6	392, 988, 1245
	3 Octaves	Major	G4, B5, D7	392, 988, 2349
		Minor	G4, B♭5, D7	392, 932, 2349
		Augmented	G4, B5, D♯7	392, 988, 2489
C5	1 Octave	Major	C5, E5, G5	523, 659, 784
		Minor	C5, E♭5, G5	523, 622, 784
		Augmented	C5, E5, G♯5	523, 659, 831
	2 Octaves	Major	C5, E6, G6	523, 1319, 1568
		Minor	C5, E♭6, G6	523, 1245, 1568
		Augmented	C5, E6, G♯6	523, 1319, 1661
	3 Octaves	Major	C5, E6, G7	523, 1319, 3136
		Minor	C5, E♭6, G7	523, 1245, 3136
		Augmented	C5, E6, G♯7	523, 1319, 3322
G5	1 Octave	Major	G5, B5, D6	784, 988, 1175
		Minor	G5, B♭5, D6	784, 932, 1175
		Augmented	G5, B5, D♯6	784, 988, 1245
	2 Octaves	Major	G5, B6, D7	784, 1976, 2349
		Minor	G5, B♭6, D7	784, 1865, 2349
		Augmented	G5, B6, D♯7	784, 1976, 2489
	3 Octaves	Major	G5, B6, D8	784, 1976, 4699
		Minor	G5, B♭6, D8	784, 1865, 4699
		Augmented	G5, B6, D♯8	784, 1976, 4978

The Chord Discrimination test used a three interval two alternative forced choice odd-ball (3I-2AFC) paradigm. Participants were presented with sets of three stimuli, beginning on the same chord root and spanning the same number of octaves. The first stimulus was the standard, a major chord, and the 2nd or 3rd was the target, either a minor chord or augmented chord. Thus the standard and target differed only on one note that changed by one semitone. The computer interface comprised of three response buttons, each lighting up in turn as the stimuli played. The participant's task was to click or touch the button representing the stimuli that was different to the other two. Feedback was given in the lower right hand corner of the screen, in the form of a green thumbs-up for a correct answer, and a red thumbs-down for incorrect.

These sets of stimuli were presented in eight blocks comprising thirty sets each. Each block used the same chord root (either C4, G4, C5 or G5) with separate blocks for Simultaneous and Sequential stimuli. Each block was made up of 6 possible comparisons (Major-Minor 1 Octave, Major-Augmented 1 Octave, Major-Minor 2 Octave, Major-Augmented 2 Octave, Major-Minor 3 Octave, and Major-Augmented 3 Octave). Each comparison was presented five times per block. Approximately 5 minutes of training was delivered before commencing the test, which comprised one block of Simultaneous and one block of Sequential sets covering all of the stimuli.

3.2.3.2 Vowel-Consonant-Vowel (VCV) test

Pre-recorded vowel-consonant-vowel stimuli were used and they were stored as files in a .wav format with a 22 kHz sampling frequency. These consonants used were naturally occurring in British English and presented in an intervocalic formation. The speaker was a female native speaker of British English. Consonants used were /b/, /tʃ/, /d/, /dʒ/, /f/, /g/, /h/, /k/, /l/, /m/, /n/, /p/, /r/, /s/, /ʃ/,

/t/, /Ɵ/, /v/, /w/, /j/, and /z/ and vowels were /ɑ/, /i/ and /u/. Four tokens of each consonant in each of these intervocalic environments were available. Twelve lists of different presentation orders were available each one containing 63 tokens. Different list orders were given to different participants. Each consonant in each vowel environment was presented once and they were selected from one of four available utterances of that token. Presentation level was set to the most comfortable level for each participant.

The VCV test had a computer response interface with 20 buttons, each displaying an orthographic representation of the 20 consonants (CH for /tʃ/, J for /dʒ/, SH for /ʃ/, TH for /Ɵ/, and Y for /j/). The consonants were displayed in the context of a one-syllable word. Stimuli were presented in lists of 63, and responses were made by selecting one of the buttons by click or touch. Once a response was given, whether correct or incorrect, the correct answer would light up. No training was given.

3.3 Results

3.3.1 Chord Discrimination Test

To account for the chance level in the task, each participant’s overall percentage of passes for each test was converted to a d-prime score according to Hacker and Ratcliffe (1979). In order to assess the test-retest validity of the chord test, an intraclass correlation was performed between the first and second run of the test for all participants who had carried it out twice, and the second and third run for all who had carried it out three times. A significant degree of reliability was found between the first and second run of the test. The average measure ICC was 0.42 with a 95% confidence interval from 0.33 to 0.50 ($F^{(719,719)} = 1.72$, $p<.001$).

A repeated measures ANOVA was carried out with the within subject factors of Presentation Mode (Simultaneous, Sequential), Chord Contrast (Major-Minor, Major-Augmented), Chord Root (C4, G4, C5, G5), and Octave Span (One, two, three). Each of the main effects from the analysis will be reported under a separate heading and the interactions reported at the end.

3.3.1.1 Factor 1: Presentation Mode (Simultaneous, Sequential)

There was a significant main effect of Presentation Mode ($F^{(1,15)} = 6.4$, $p = 0.02$). Figure 3.2 shows that the distribution of scores was much larger for the Simultaneous presentation than for the Sequential, with higher scores achieved in the Simultaneous presentation.

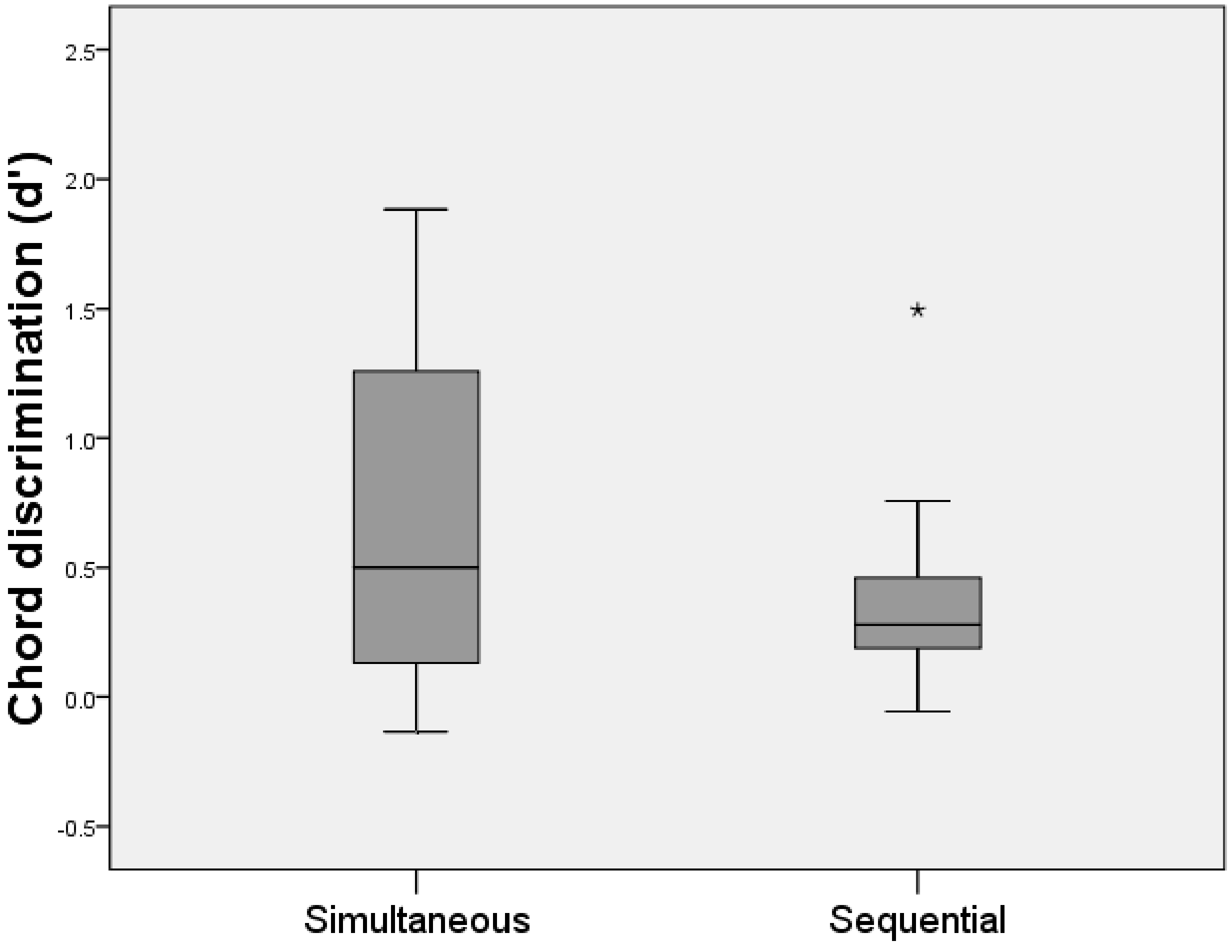


Figure 3.2: Boxplot of the distributions of scores (d') for the two Presentation Mode conditions. Dark horizontal lines represent the median, with the box representing the 25th to 75th percentiles, the whiskers the minimum and maximum values (apart from outliers), and an extreme outlier represented by a star.

3.3.1.2 Factor 2: Chord Contrast (Major-Minor, Major-Augmented)

There was no significant main effect of Chord Contrast ($F^{(1,15)} = 2.26$, $p = 0.15$). Figure 3.3 shows that the distribution of scores was larger for participants identifying the augmented rather than the minor chord, but medians were very similar.

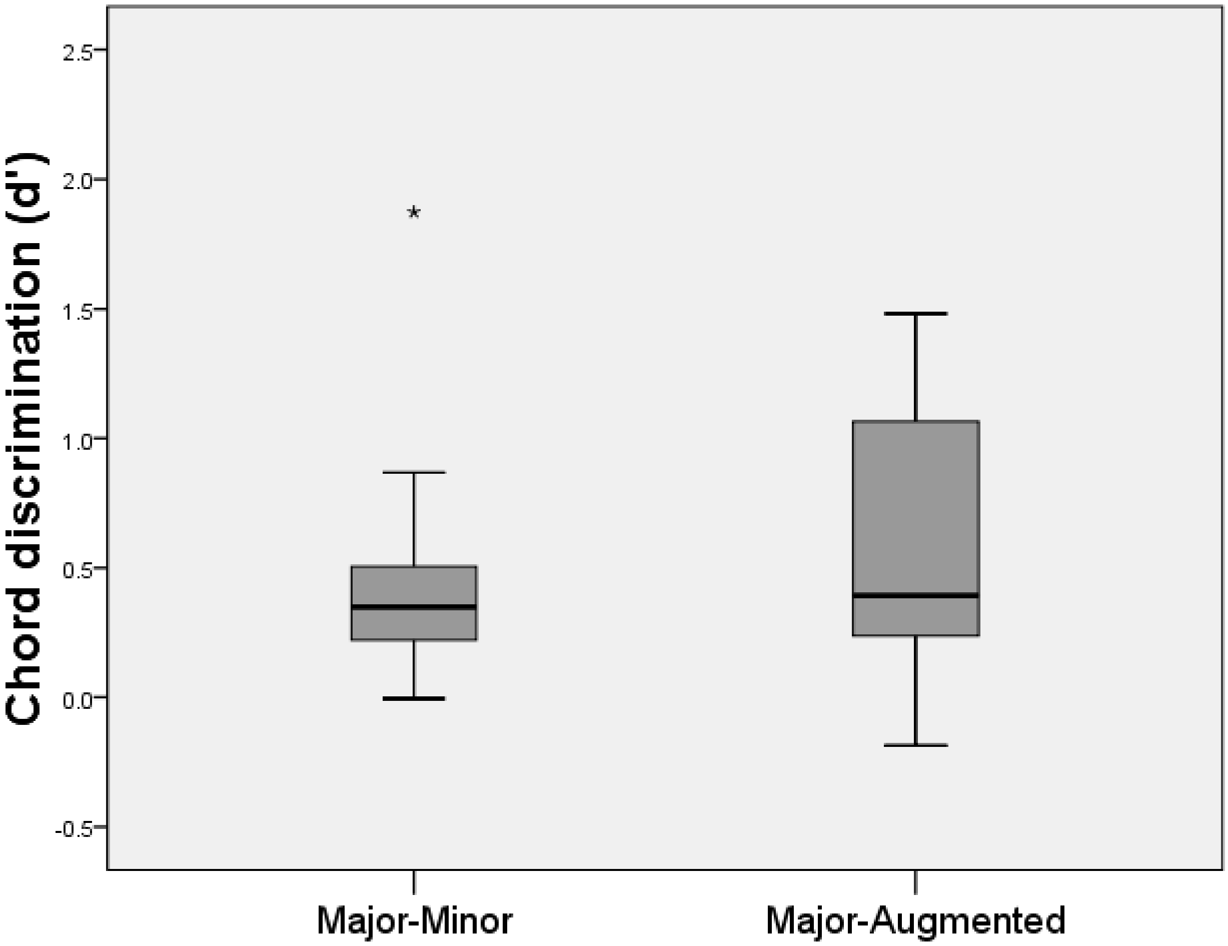


Figure 3.3: Boxplot of the distributions of scores (d') for the two Chord Contrast conditions. An extreme outlier is represented by a star.

3.3.1.3 Factor 3: Chord Root (C4, G4, C5, G5)

There was no significant main effect of Chord Root ($F^{(3,45)} = 0.896$, $p = 0.45$). Figure 3.4 shows the distribution of scores each of the four chord roots.

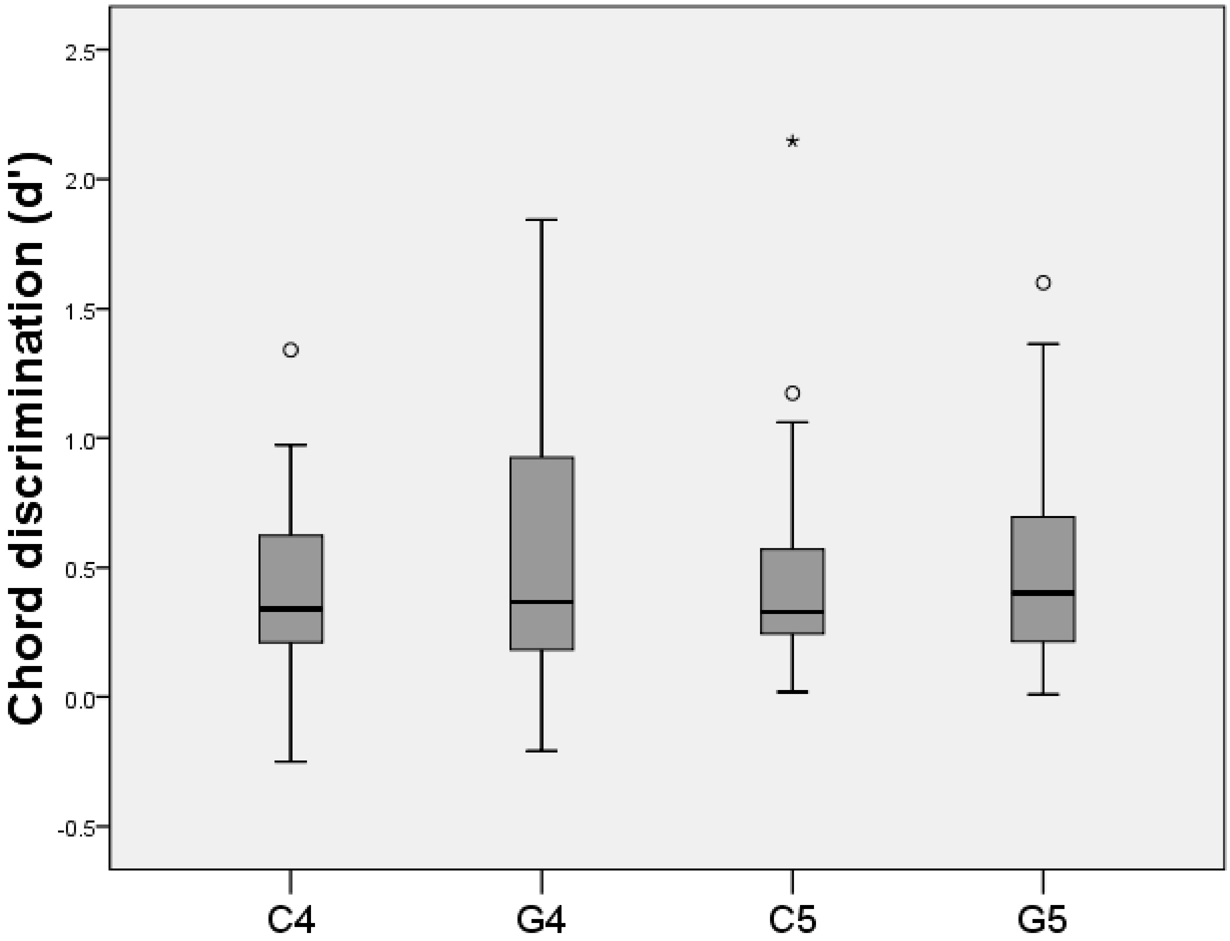


Figure 3.4: Boxplot of the distributions of scores (d') for the four Chord Root conditions. Circles represent outliers.

3.3.1.4 Factor 4: Octave Span (One, two, three)

There was a significant main effect of Octave Span (F $^{(2,30)}$ = 3.34, p = 0.049). Figure 3.5 shows the distribution of scores for all octave span conditions. Post-hoc tests were conducted using a Least Significant Difference test, and showed that there was a significant difference between the One Octave and Three Octaves condition (MD = -2.53, SD = 0.112, p = 0.039).

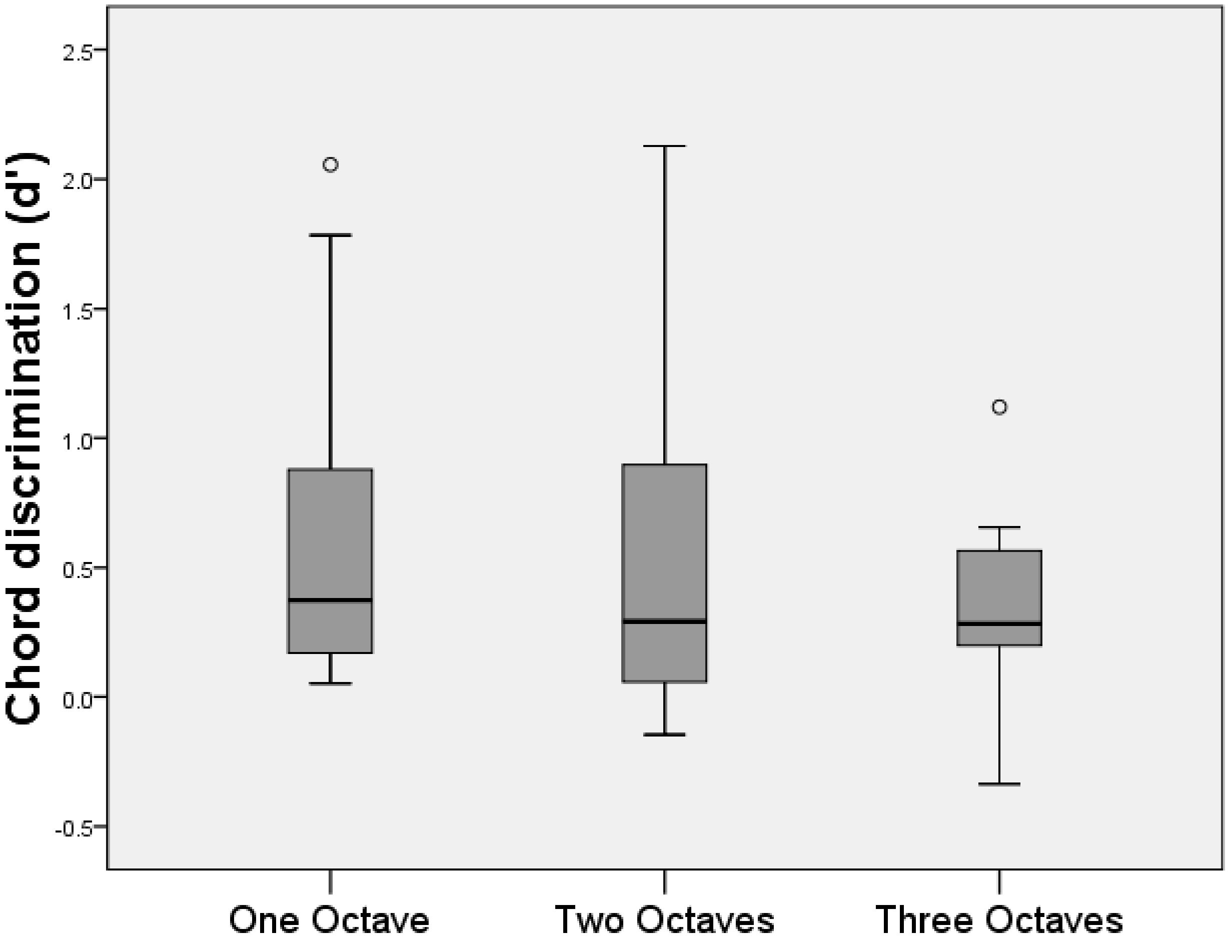


Figure 3.5: Boxplot of the distributions of scores (d') for the four Octave Span conditions. Circles represent outliers.

3.3.1.5 Interactions

There was a significant interaction between Presentation and Octave Span ($F^{(2,15)} = 1.68$, $p = 0.02$). Figure 3.6 shows the distribution of scores for the Simultaneous and Sequential presentations of chords, separated by Octave Span. It shows that median scores fell slightly in the Simultaneous condition as the number of octaves increased, but in the Sequential condition, scores rose as the number of octaves increased.

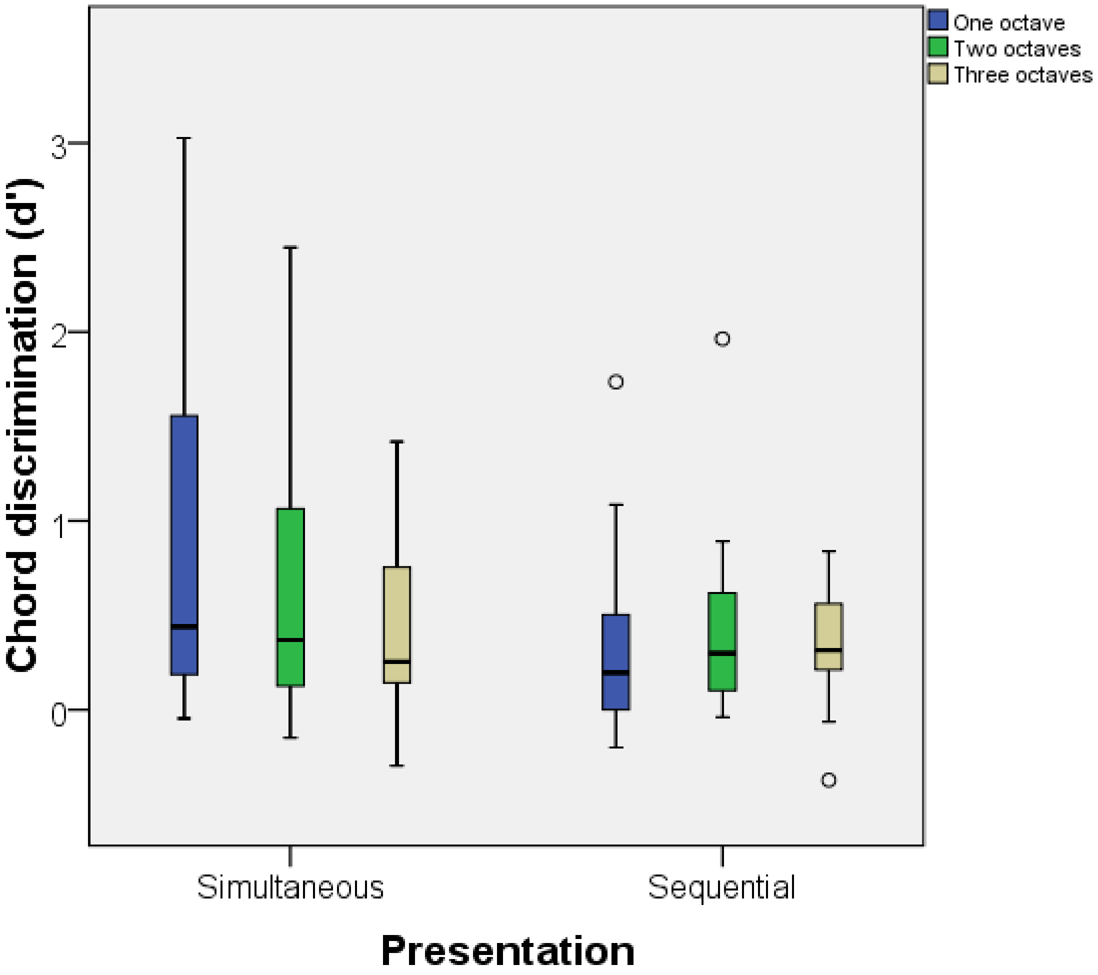


Figure 3.6: Boxplot of the distributions of scores (d'), separated by Presentation and Octave Span.

3.3.1.6 Frequency of changing note

An additional analysis was conducted based on the frequency of the note that changed. This was done because for each Chord Root condition, the frequency of the changing tone might vary widely due to the Octave Span condition. Therefore, four frequency bands were identified representing the range of frequencies of the changing tone. These bands were 300 to 700 Hz, 700 to 1400 Hz, 1400 to 2500 Hz and 2500 to 5000 Hz. These bands were roughly based upon the frequency distribution in a cochlear implant with the intention of separating an electrode array into four spectral regions with the same number of channels in each region. The Advanced Bionics device with 16 electrodes was used to derive the calculation but it would approximate the distribution for all cochlear implant devices. Figure 3.7 shows the distribution of scores for each participant for each frequency band.

Welch's F test was conducted to account for the different number of conditions on each frequency and to compare the d prime scores in each frequency range and for each device type. This showed no significant main effect of frequency range (F (3,68) = 0.82, p = 0.49).

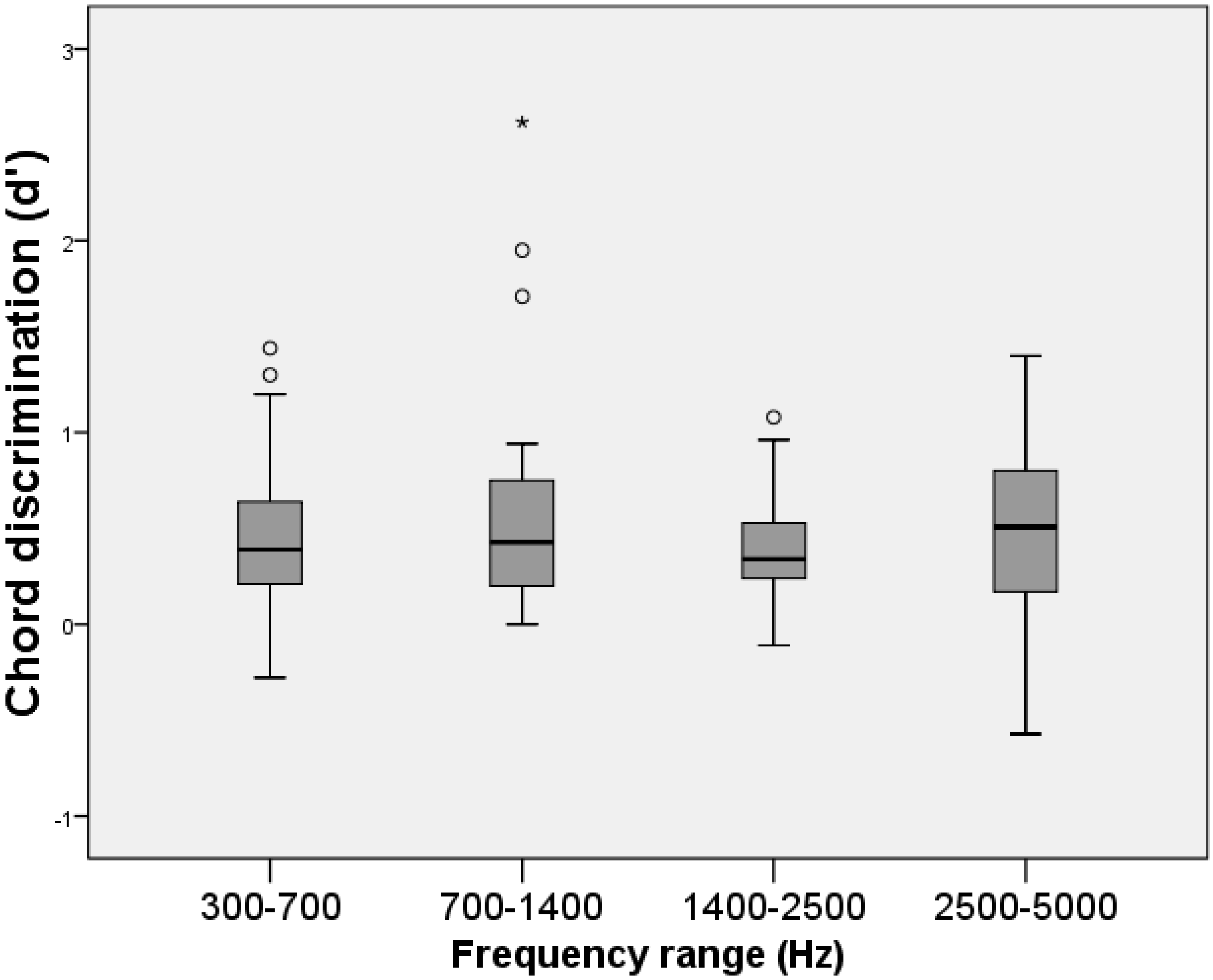


Figure 3.7: Box plot of the distributions of scores (d') for the four frequency ranges.

3.3.2 VCV tests

VCV percentage correct scores were converted to d prime scores according to Hacker & Ratcliff (1979). Individual performance of each participant on correctly identifying the voicing, manner and place of the consonants, as well as overall correct answers, is shown in figure 3.8. Performance on the three consonant features as well as overall correct answers is shown in figure 3.9.

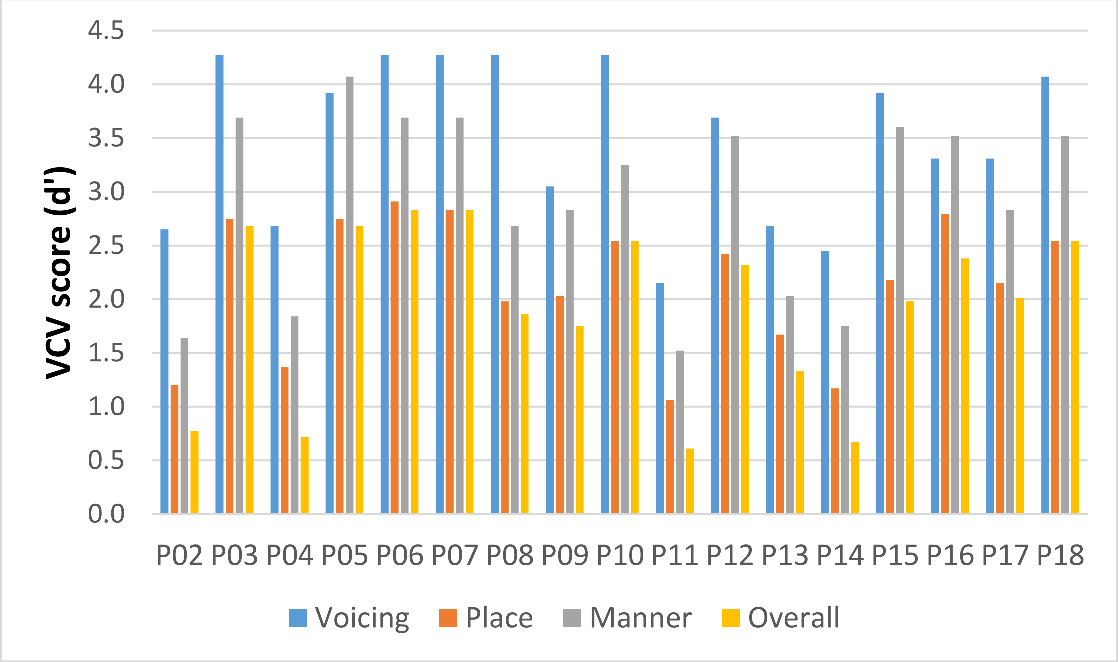


Figure 3.8: Individual correct consonant identification (d') for 17 participants (P01 did not complete the VCV test).

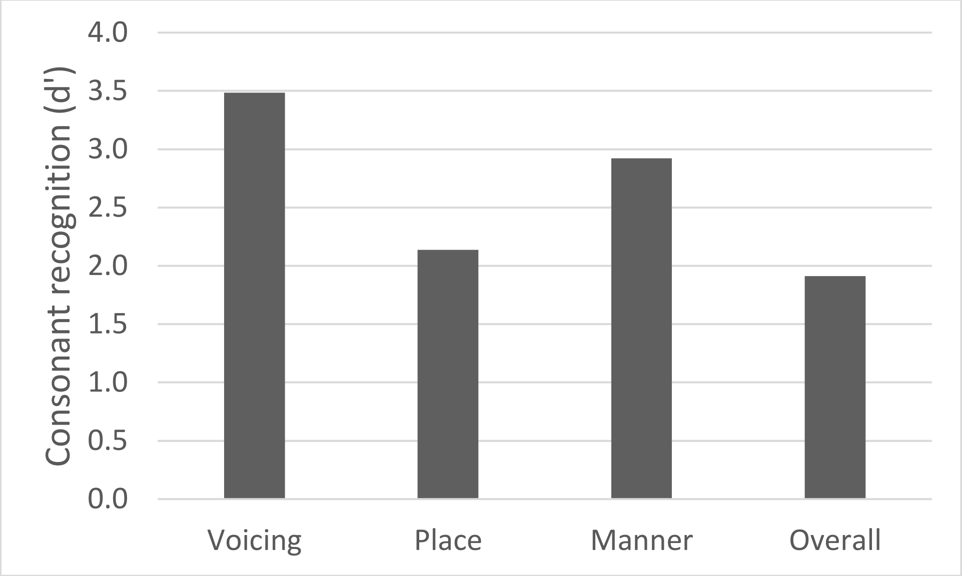


Figure 3.9: Performance on voicing, manner, and place as well as overall consonant recognition.

Overall chord tests scores and VCV percentage correct scores (d’) were not correlated (r = -0.36, p = 0.159). There was a significant correlation between scores on the One Octave condition and VCV scores (r = 0.6, p = 0.01). A scatterplot of this correlation can be seen in figure 3.10.

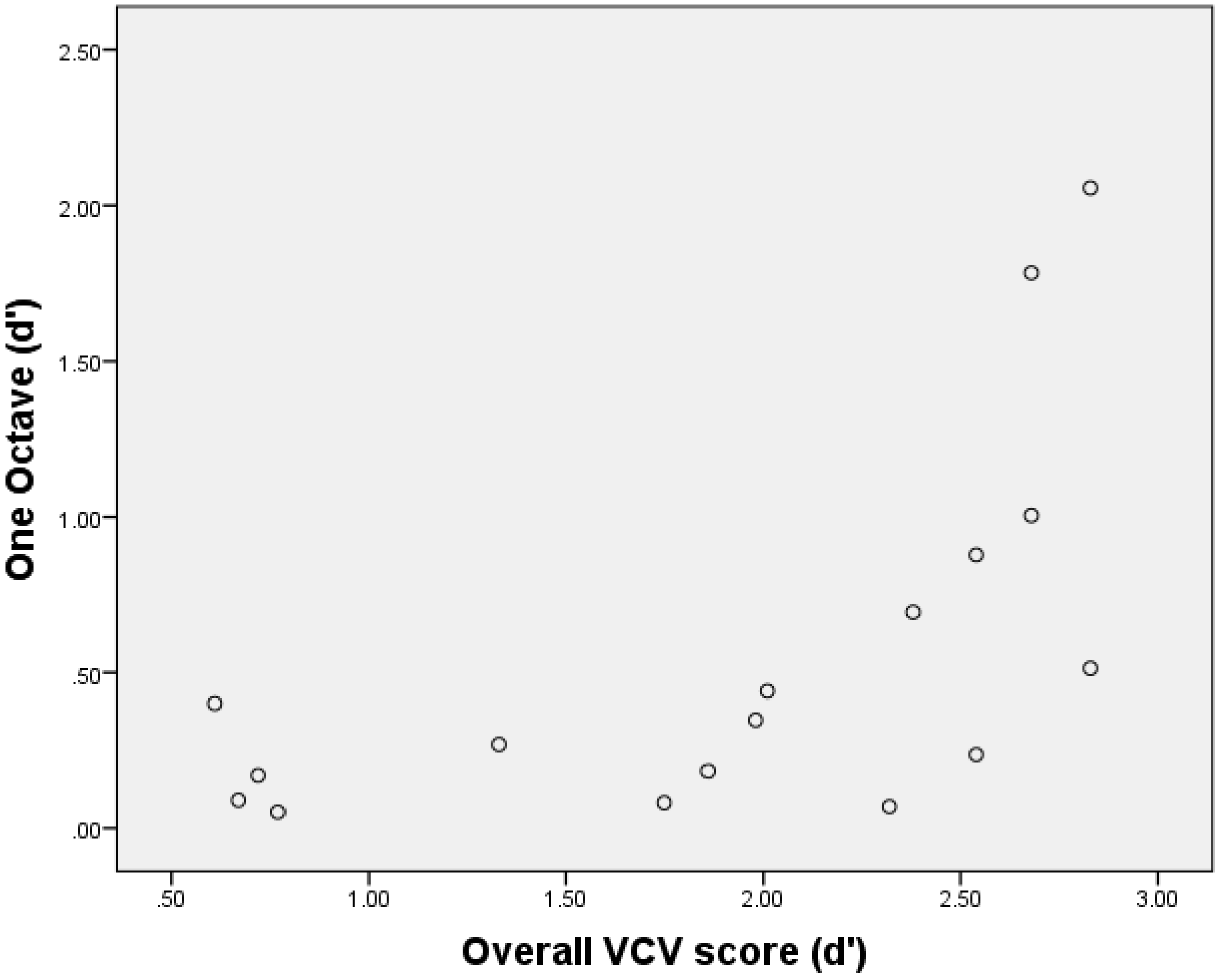


Figure 3.10: Scatterplot of the correlation between the d' scores for the One Octave condition of the chord test, and the overall VCV scores.

3.4 Discussion

The pilot study described here aimed to examine pitch perception in a musical context for CI users. Musical chords are a very common aspect of Western music, but they have not been widely used in tests of pitch or music perception for CI users. In this study, a number of different chord parameters were examined to discover if they can provide useful information regarding CI users' pitch discrimination in musical contexts.

One aim of this study was to expand and develop upon the musical chord test devised by Vongpaisal et al. (2006). In their study, children and adolescents with CIs were asked to identify if two musical chord were the same or different. In that study, chords were presented only in a sequential presentation. In the present study, Sequential and Simultaneous presentations were compared. Performance in the Simultaneous chord task was significantly better than performance in the Sequential task. In music, chords are very commonly presented with notes played simultaneously, and are reported as having different emotional connotation. In particular, major chords are generally reported as sounding happy, and minor chords sad (Crowder, 1984; Peretz et al., 1998; Bowling, 2013). However, cuing into the different emotional associations that the chords evoke and differentiating them accordingly, would require a very precise frequency to place map which is likely to be unattainable for most CI users.

It is possible that auditory memory may also be playing a part in the better performance on the Simultaneous task. During testing, many participants reported that the length of the stimuli made it difficult to remember the standard once all the stimuli had been heard. It is possible that the longer duration of the Sequential stimuli placed a burden on participants' short term memory which was not encountered when listening to the Simultaneous stimuli. Miller (1956) identified a limit on the number of items that can be stored in short term memory as 7 +/- 2. As each sequence in the Sequential stimuli contained five tones, the total number to be remembered in each trial was fifteen, which may have strained the limits of the participants' short term memory. However, the process of chunking – assigning items into meaningful groups – has been shown to improve the number of items that can be recalled. In the present study, this process should come into effect with training, as the fifteen separate tones are grouped into three meaningful chunks. Furthermore, each of these chunks begins with the same tone, and establishment of such a reference tone has been shown to facilitate memory for all tones in a set (Cohen, 2005).

Previous studies have shown that CI users have difficulty identifying a number of tones when presented acoustically, often reporting that they hear two or three simultaneous tones as a single tone (Donnelly et al. 2009). This can be linked to the phenomenon of tonal fusion, in which simultaneous concurrent tones are heard as components of a single complex tones (Huron, 1991). Even NH listeners can have difficulty discerning the number of tones in a presentation of simultaneous tones (Huron, 1989; Ockelford, 2012). It is therefore possible that the stimuli in the Simultaneous presentation were heard by some participants as a single tone. In addition, CI users have been shown to have difficulty identifying a changing note in a melodic sequence, even if the frequency difference between the two notes is one they are able to detect when the notes are presented in isolation (Pressnitzer et al., 2005). This suggests that it is more difficult for CI users to detect pitch changes when the tones are presented in the context of a melody, than it is when the tones are presented in isolation. To further explore this aspect of CI users' pitch perception, the amended test battery included a pitch ranking test, presenting tones in the same frequency ranges as the Chord Discrimination Test, and therefore allowing assessment of participants' frequency difference limens at the same frequency ranges used in the chord test.

Previous research has found that CI users have trouble discriminating pitch differences as small as one semitone (Gfeller et al., 2002; Sucher & McDermott, 2007; Galvin et al., 2007). Identifying a change of one semitone was certainly a challenging task for the participants of the present study, with many performing below chance, but there were a number of participants who were able to discriminate this small difference with relative ease. Despite this, there was no significant difference between scores based upon the Chord Contrast factor. According to the hierarchy of tones theory by Krumhansl and Cuddy (2010), it would be expected that the change from a major chord to an augmented chord would be more easy to perceive, as it involves a change in a note higher on the hierarchy than the change from major to minor. However, given the difficulty for CI users discriminating a one semitones change, it is difficult to make any conclusions based on this. Therefore, in the amended test battery, changes of two and three semitones will be added to the battery.

No significant effect of spectral region was found in the study, either by the chord root of the chord or the frequency of the changing note of the chord. However, it is not possible from these results to make any reliable conclusions, as both factors were flawed in design. The Chord Root factor did not take into account the frequency of the changing note, which could be one or two octaves higher than the root note; and the four levels of the frequency change factor did not contain equal numbers of tests. These concerns were addressed in the amended test battery. As performance on the tests declined as the octave span increased, the amended test battery will feature chords whose notes all fall within an octave of the chord root. In this way, the root note of the chord will immediately identify the octave that the changing note falls in.

There was a significant difference between the scores in the One Octave condition and the Three Octave condition, with a general worse performance in the Three Octave condition. It would appear that, despite involving different spectral regions, there is little perceptual benefit to be gained for this particular task purely from spreading the notes of the chord over several octaves. This is supported by the finding that the only correlation found between scores on the VCV test and the Chord Discrimination Test was for the One Octave condition. This could be an indication of an individual's spectral resolution. Figure 3.13 showed that, for d' scores above 0.5 on the chord test in the One Octave condition there is a steady increase in the associated VCV score. Recognition of consonants relies on spectral shape and slow temporal envelope cues (Faulkner 2006; Donaldson & Kreft 2006, Vershuur, 2009). This suggests that some participants were able to make use of the limited spectral information available from the CI both for discerning the pitch change in the musical chord and for correctly identifying the consonant.

3.5 Summary of findings

1. CI users were better able to discriminate differences between musical chords when the notes are presented simultaneously rather than sequentially

2. Some CI users were able to discern a one semitone difference between chords

3. No significant performance was seen based on the differing frequency ranges of the stimuli.

4. No pitch perception advantage was found when the notes of the chord were spread across several octaves, compared to keeping them within one octave.

5. Pitch discrimination within a single octave was correlated with VCV scores, which could be in indicator of some CI users being able to make better use of the limited spectral information available from the CI.

3.6 Amendments to the pilot study test battery

Results of the pilot study informed decisions about the elements needed in the Chord Discrimination Test to be used in the main phase of the study. The Chord Discrimination Test devised for this pilot study was shown to be appropriate to provide information about CI users' pitch perception in simultaneous and sequential contexts in musical chords. However, results highlighted a number of necessary amendments which were made to the test battery going into the main phase of the study.

1. The chord tests should take into account the frequencies of the changing tone which the participant has to identify. The pilot study tests were designed around the root note upon which the chord was created. However, due to the Octave Span condition, this resulted in an uneven spread of the actual frequencies whose

change was to be detected. A more useful test would divide the changing tone evenly across all frequency bands available to the participant. This would provide a stronger indication of the participants' abilities to identify changing pitches across the spectrum of their hearing.

2. The Octave Span factor was removed as a parameter because increasing octave span did not provide any benefit to the participants' abilities to discriminate between pitches. All chords in the amended test battery were presented in a single octave span, with root notes of C4, C5, C6 and C7 to ensure a wide range of frequencies was covered.

3. With many participants performing at chance, the current test of discriminating one semitone was deemed to be too difficult for many CI users. The main study testes pitch discrimination at differences of two and three semitones in addition to one.

4. Pure tones are rarely heard in everyday environments, particularly music. To get a more accurate view of pitch perception in musical contexts, the main study uses complex tones (simulated piano tones) as well as pure tones.

5. The VCV tests used in the pilot study indicated a correlation between consonant recognition and the ability to recognise chord changes in the One Octave note span. However, consonant recognition is only one aspect of speech recognition. Sentence recognition tests were added to the battery in order to give more information about the relationship between the participants' pitch and speech perception abilities. Examining speech perception alongside music

perception can add insight into the overall listening experience of a CI users. In a study looking at factors which might predict music perception and appreciation in CI users, Gfeller et al. (2008) found that speech recognition was not a predictive factor in a number of music assessments, including pitch ranking, melody and timbre recognition, and music appraisal. These results would suggest that it is important to examine both aspects in order to obtain a complete view of the success of a CI user's listening experience.

6. The pilot study results showed a great deal of individual difference between participants in their ability to detect the changes in musical chords. Because of this, a pitch ranking test was added to the test battery, so that each participants pitch discrimination thresholds in particular frequency ranges could be compared to their results on the musical chord test in the same frequency region.

Chapter 4 – Pitch perception in musical chords for CI users: comparisons of pure and complex stimuli, speech perception and pitch ranking

4.1 Introduction

The ability to accurately perceive pitch is important for the appreciation and enjoyment of music, because it conveys information important for melody, harmony and timbre (Schnupp et al., 2011). The pilot study described in chapter 3 used pure tone stimuli to examine pitch perception in musical contexts for CI users. However, musical instruments and singing voices, whether heard as solo performance or in combination, are complex sounds. The extraction of pitch from complex sounds places more demands on the auditory system than for pure tones. Complex tones are comprised of a number of different frequency components in combination, and account for the vast majority of sounds heard on a daily basis.

Extracting pitch from complex sounds is difficult for CI users. Processing strategies typically divide the input sound into a number of bandpass filters, each representing a specific spectral region, followed by extraction of the temporal envelope which is used to modulate a train of biphasic pulses which are delivered to the electrodes. Due to these features of the sound processing strategies, there are two mechanisms available to CI users in the perception of pitch. Place pitch is subject to the position of the electrode in the cochlea to which the stimulus is delivered, and rate pitch relies on the rate at which the train of pulses is delivered (McDermott, 2004).

For a CI user, spectral information is provided by stimulation at different electrode sites, which means that information relating to place pitch is limited by the number and location of the physical electrode contacts available for stimulation. Temporal information is limited by the sound processing strategy, which in many cases removes the temporal fine structure cues. In a study examining the differing contributions of place and temporal information to pitch perception in CI users, Zeng (2002) measured changes in frequency difference limen for rate of stimulation on a single electrode pair. It was demonstrated that temporal pitch cannot be discriminated by CI users at rates higher than 300 Hz. For sounds above 300 Hz, CI users must rely chiefly on place pitch obtained from spectral information for their pitch perception. However, the limited frequency selectivity available makes it extremely difficult or even impossible for CI users to resolve harmonics in complex tones (Moore & Carlyon, 2005).

Research looking into the perception of the pitch of complex tones in CI users has shown deficits in comparison to NH listeners. In a study by Sucher & McDermott (2007), 10 NH listeners and 8 CI users were asked to pitch rank complex tones consisting of sung vowels. The interval between the F0 of the two stimuli to be pitch-ranked was either one or six semitones. CI users were found to be significantly worse than NH listeners at this pitch ranking task, with only 49% of CI users able to successfully pitch rank at a one semitone difference, which was significantly lower than the NH listeners at 81%. At six semitones, CI listeners scored better at 60% correct, but still significantly lower than the NH listeners at 89%. Within the NH group, significantly better performance was seen in those who had a higher level of musical experience, but all NH listeners scored significantly better than CI listeners on the tests regardless of their level of musical experience.

Gfeller et al. (2002) also carried out a study comparing the perception of complex tones in CI users and NH listeners. The stimuli for this experiment were simulated grand piano notes, ranging over three octaves (36 semitones) from 73Hz to 553 Hz. Participants were presented with two tones and had to indicate whether the second was higher or lower than the first. Eight NH listeners and 46 CI users took part. Results showed that while some listeners were able to detect a pitch change in a complex tone of one semitone, others needed as much as two octaves to do so.

Such deficits in the perception of the pitch of complex tones make it difficult for CI users to recognize melodies which are made up of complex tones. Singh et al. (2009) tested CI users on their ability to recognize melodies comprised either of pure tones or complex harmonic tones. They found a significantly better performance for the recognition of pure tone melodies, particularly in higher frequencies (414 – 1046 Hz, approximately equivalent to G♯4 to C6). Increasing the number of activated electrodes only improved melody recognition in this higher frequency range.

The research to date highlights the difficulties faced by CI users in the perception of complex tones. As the vast majority of musical sounds are complex tones it is essential to explore this aspect in a test battery to assess pitch perception within music. Additionally, it is important to examine the effect that the musical context has on a CI user’s pitch perception. Pressnitzer et al. (2005) carried out a study in which each participant’s pitch ranking ability was initially assessed, revealing that the CI users taking part could pitch rank at differences between 2 and 7 semitones. In the experimental task, a four note chromatic melody was presented twice, with one note changing in the second presentation. Identifying the changed note proved impossible for most CI users, even when the interval between the changing notes was larger than each individual listener’s pitch ranking threshold. A NH control group performed at ceiling in the same task.

It is also important to ascertain the effects a particular sound processing strategy may have on the perception of music. A number of CI device manufacturers have devised processing strategies with the aim of improving pitch perception for the CI user. In ‘Virtual Channel’ processing strategies such as AB’s HiRes120, the proportion of current delivered simultaneously to two electrodes is adjusted in order to cause intermediate pitches to be perceived (Townshend et al. 1987, Firszt et al., 2007). In tests of direct electrode stimulation, the HiRes120 strategy has been shown to provide potentially up to nine intermediate pitches (Donaldson and Kreft (2005). Another strategy specifically devised to improve the perception of pitch is MED-EL’s Fine Structure Processing strategy (FSP). In this strategy, the lower channels utilize channel specific sampling sequences, each of which is a series of stimulation pulses which has an instantaneous repetition rate equal to the instantaneous fine structure frequency of the signal in that frequency range. The remaining channels employ a sequential implementation of the so-called virtual channel strategy (Hochmair et al., 2006). This strategy has been shown to provide significant improvements compared to the CIS strategy in the perception of musical rhythm, melody and timbre (Arnoldner et al., 2007). However, when learning effects are controlled for, these benefits are not seen (Magnessen, 2011).

Examining speech perception alongside music perception can give insight into the overall listening experience of a CI users. CIs are optimised for speech perception, and studies have shown that the temporal envelope cues provided by the CI can be sufficient for the recognition of sentences and phonemes in quiet (Nie et al., 2006). Spectral information is important for understanding speech in noise, and other studies have found correlations between music perception and perception of speech in noise for CI users (Gfeller et al. 2002, 2007). This suggests that improving music perception in CI users could also benefit them in other areas such as perception of speech in noise (Drennan & Rubinstein, 2008). However, in a study looking at factors which might predict music perception and appreciation in CI users, Gfeller et al. (2008) found that speech recognition was not a predictive factor in a number of music assessments, including pitch ranking, melody and timbre recognition, and music appraisal. In the pilot study detailed in chapter 3, there was a significant correlation between participants' scores on the VCV test, and their scores on the Chord Discrimination Test for chords with notes spanning within a single octave. These results would suggest that it is important to examine speech perception alongside music perception in order to obtain a complete view of the success of a CI user's listening experience.

In the present research, the expanded version of the Chord Discrimination Test was used with the aim of exploring pitch perception of both pure and complex tones for CI users in the context of musical chords, and examining the relationship between pitch perception and speech perception. The following research questions were explored:

1. Are differences in musical chords easier to hear when presented as pure tones or complex tones?
2. Are CI users better at perceiving changes in musical chords presented simultaneously or sequentially?
3. Is a change in a musical chord easier to detect when the changing note is the top note or the middle note of the chord?
4. Are some spectral regions easier for detecting frequency differences?
5. Given that identifying the changed chord when one note was altered by one semitone was difficult for CI users in the pilot test, will scores improve when the chord changes by two or three semitones?
6. Are there device-specific patterns to pitch perception?
7. Does pitch discrimination ability differ when the same frequencies are presented within and outside of a musical context?
8. What is the relationship between perception of pitch in musical contexts and speech perception?

4.2 Materials and Methods

Ethical approval was sought from the UCL Research Ethics Committee (Application 3523/003) and was granted by the Chair in January 2014.

4.2.1 Participants

There were 17 participants in total, ranging in age from 34 to 77 years old (13 female, 4 male). Table 4.1 gives the age, gender, device, sound processing strategy, and duration of CI use for each participant.

Table 4.1: Demographic information for 17 CI users, accounting for 18 implanted ears (P05 and P11 are the same participant), including device, sound processing strategy, age, and duration of CI use.

Participant	Gender	Device	Sound processing strategy	Age	Duration of CI use
P01	F	AB Naida	HiRes 120	38	4 years
P02	F	Cochlear Nucleus 5	ACE	49	3 years
P03	F	MED-EL Opus 2	FSP	60	2 years
P04	F	Cochlear Nucleus 5	ACE	69	6 years
P05	M	Cochlear 3G	ACE	77	17 years
P06	M	MED-EL Opus 2	FSP	66	2 years
P07	F	MED-EL Opus	FSP	61	3 years
P08	F	Cochlear Freedom	ACE	36	13 years
P09	M	AB Naida	HiRes 120	67	5 years
P10	M	AB Naida	HiRes 120	38	13.5 years
P11	M	AB Naida	HiRes 120	77	17 years
P12	F	AB Naida	HiRes 120	34	6 years
P13	F	Cochlear	ACE	62	5 years
P14	F	MED-EL Opus	FSP	69	10 years
P15	F	AB Naida	HiRes 120	63	6.5 years
P16	F	Cochlear	ACE	61	17 years
P17	F	MED-EL	FSP	35	14 years
P18	F	MED-EL Opus	FSP	67	6 years

Eleven of these participants had taken part in the pilot phase. The rest were recruited from a pool of adults with CIs who had registered on a participant database at the UCL Ear Institute, or were referred by other participants. One participant was implanted with a Cochlear device in the right ear and an Advanced Bionics device on the left. This participant was tested twice with each ear separately, and therefore accounts for two datasets (P05 and P11). Therefore there were 18 ears tested in total and these were distributed as six ears using devices from each of Cochlear, MED-EL and AB. These participants were paid £15 for their participation, and their travel expenses were reimbursed.

4.2.2 Apparatus

The Chord Discrimination Test was delivered using a script in Apex 2.1 Unified Version (a psychophysical platform for presenting stimuli to NH and CI listeners; Geurts & Wouters, 2000). The script was a modified version of the "Constant Stimuli" module that was available from the developers. Adaptive pitch perception test was run using the "Adaptive" module. VCV tests and IHR sentence test were delivered and controlled using a MATLAB script.

Participants were tested in a quiet room. Sounds were presented through Sennheiser HD414 headphones connected to a Dell Latitude touch-screen laptop.

Presentation level for all tests was set at the most comfortable level for each participant, which they ascertained during the training phase.

4.2.3 Stimuli and procedure

Each participant attended for two sessions of approximately 2 to 3 hours long each. The same tests (Musical Chord Discrimination, Pitch ranking, VCV and IHR sentence recognition, in that order) were repeated at each session. The only exceptions to this pattern were for two participants who struggled to complete the test battery in one session. For these participants, the testing sessions were split into three visits rather than two.

4.2.3.1 Chord Discrimination Test

Stimuli for the Chord Discrimination Test were prepared in MATLAB R2012a with a 44.1 kHz sampling frequency, duration of 0.5s and cosine onset/offset ramps of 0.1s, and were saved in the .wav format. All stimuli were calibrated to have equal root-mean-square average levels and were presented over Sennheiser 414 headphones at a comfortable listening level for each participant. A small degree of level rove was applied at ±1dB per stimulus, to remove the possibility of participants using level cues to discriminate between the stimuli.

The stimuli can be described by the factors detailed in the following sections:

Factor 1: Tone (Sinusoid, Piano Simulation)

Sinusoid tones were created with one single harmonic, and Piano Simulation tones were created with 20 harmonics, to more closely resemble the spectral shape of piano notes.

Factor 2: Presentation Mode (Simultaneous, Sequential)

The Simultaneous and Sequential Presentation Modes remained unchanged from the pilot study, in order to continue to examine differences in pitch perception for CI users in these two modes. There were two groups of stimuli: Simultaneous and Sequential. For Simultaneous stimuli, three 0.5s pure tones making up the notes of each chord were presented simultaneously. For Sequential stimuli, the same sinusoids or simulated piano tones were concatenated in an ascending then descending order, with 0.1s of silence between each tone, following Vongpaisal et al. (2006) (i.e. five notes in total).

Factor 3: Chord Change: (Middle Note, Tope Note)

This factor was slightly different from the pilot study, in which all chord changes differed by only one semitone. This was too small a difference for many CI users to detect. Therefore, in this study, difference of one, two or three semitones were used. The standard in each trial was a major chord. The odd one out either followed the pattern of a minor chord (in which the middle note was lowered) or an augmented chord (in which the top note was raised). However, the number of semitones changing in the odd one out varied according to the Semitone Difference factor (see table 4.2 below). Therefore, the labels Minor and Augmented no longer accurately describe the chords being used. The label Middle Note will be used for chord changes in which the middle note drops by a number of semitones and Top Note for chord changes where the highest note is raised by one semitones.

Table 4.2: List of frequencies used in the Chord Discrimination Test (Hz)

Chord root	**Chord**	**Semitone difference**	**Bottom note (Hz)**	**Middle note (Hz)**	**Top note (Hz)**
C4	Major		262	330	392
	Middle Note	1	262	311	392
	Middle Note	2	262	292	392
	Middle Note	3	262	277	392
	Top Note	1	262	330	415
	Top Note	2	262	330	440
	Top Note	3	262	330	466
C5	Major		523	659	784
	Middle Note	1	523	622	784
	Middle Note	2	523	587	784
	Middle Note	3	523	554	784
	Top Note	1	523	659	831
	Top Note	2	523	659	880
	Top Note	3	523	659	932
C6	Major		1047	1319	1568
	Middle Note	1	1047	1245	1568
	Middle Note	2	1047	1175	1568
	Middle Note	3	1047	1109	1568
	Top Note	1	1047	1319	1661
	Top Note	2	1047	1319	1760
	Top Note	3	1047	1319	1865
C7	Major		2093	2637	3136
	Middle Note	1	2093	2489	3136
	Middle Note	2	2093	2349	3136
	Middle Note	3	2093	2217	3136
	Top Note	1	2093	2637	3322
	Top Note	2	2093	2637	3520
	Top Note	3	2093	2637	3729

Factor 4: Chord Root: (C4, C5, C6, C7)

The chord root – the lowest component of each chord – was either C4 (262 Hz), C5 (523 Hz), C6 (1047 Hz) or C7 (2093 Hz).

Factor 5: Semitone Difference (One, two, three)

The difference in the changing tone compared to the standard was either one, two or three semitones. The exact frequencies used in each stimulus set are shown in Table 4.2 above.

The Chord Discrimination Test used a three interval two alternative forced choice odd-ball paradigm. Participants were presented with sets of three stimuli, each beginning on the same chord root. The first stimuli was the standard, a major chord, and the 2nd or 3rd was the target. The difference between the standard and the target was one, two or three semitones. The computer interface comprised of three response buttons, each lighting up in turn as the stimuli played. The participant's task was to click or touch the button representing the stimuli that was different to the other two. Feedback was given in the lower right hand corner of the screen, in the form of a green thumbs-up for a correct answer, and a red thumbs-down for incorrect.

These sets of stimuli were presented in sixteen blocks comprising thirty sets each. Each block used the same chord root (C4, C5, C6 or C7) with separate blocks for Simultaneous and Sequential stimuli, and for sine wave or simulated piano tone stimuli. Each block was made up of 6 possible comparisons (Middle note lowering by one, two or three semitones; Top note rising by one, two or three semitones). Each comparison featured in a set 5 times per block. Approximately 5 minutes of training was delivered before commencing the test, which comprised one block of Simultaneous Sinusoid stimuli and one block of Sequential Piano Simulation stimuli.

4.2.3.2 Adaptive Pitch Discrimination Test

Frequencies for the stimuli used in the Adaptive Pitch Discrimination Test can be seen in Table 4.3.

Table 4.3: List of frequencies (Hz) used in the Adaptive Pitch Discrimination Test. The standard for each octave was F sharp (denoted in bold)

OCTAVE ROOT	**C4**	**C5**	**C6**	**C7**
F♯	185	370	740	1480
G	196	392	784	1568
G♯	208	415	831	1661
A	220	440	880	1760
A♯	233	466	932	1865
B	247	494	988	1976
C	262	523	1047	2093
C♯	277	554	1109	2217
D	294	587	1175	2349
D♯	311	622	1245	2489
E	330	659	1319	2637
F	349	698	1397	2794
F♯	**370**	**740**	**1480**	**2960**
G	392	784	1568	3136
G♯	415	831	1661	3322
A	440	880	1760	3520
A♯	466	932	1865	3729
B	494	988	1976	3951
C	523	1047	2093	4186
C♯	554	1109	2217	4435
D	587	1175	2349	4699
D♯	622	1245	2489	4978
E	659	1319	2637	5274
F	698	1397	2794	5588
F♯	740	1480	2960	5920

Stimuli for this test were sinusoids created in MATLAB R2012a, with 44.1 kHz sampling frequency, duration of 0.5 seconds and cosine onset offset ramps of 0.1 seconds. The standard for each octave was F sharp (denoted in bold on table 4.3). This is due to the fact that, when examining a scale of notes between two consecutive C notes (for example, C4 and C5), F sharp is the note which falls precisely in the middle of the two C notes. Therefore, using F sharp as the standard allows the text to examine pitch perception evenly across the octave.

The task was carried out using an Apex adaptive module (.adp) script. A one up, two down staircase model was used for a total of eight reversals, which is the standard number of reversals used in this module. Participants were presented with two pure tones of differing pitch. On the computer interface, two boxes numbered 1 or 2 were shown. The boxes lit up in turn as each tone was played. In the first test session, the participant had to identify the higher of the two tones. In the second session, the participant was asked to identify the lower of two tones. No training was given. The difference between the two tones ranged from one semitone to one octave (twelve semitones). As with the chord discrimination task, a small degree of level rove was applied at ±1dB per stimulus, to remove the possibility of participants using level cues to discriminate between the stimuli. The smallest pitch difference between two tones was one semitone; however, some participants were able to rank this difference with relative ease, and therefore did not complete the full run of eight reversals, as insufficient errors were made. For these participants, the experimenter stopped them once they had correctly identified the target in the one semitone condition fifteen consecutive times.

The frequency difference over the final six reversals was averaged and converted into semitones using the Frequency to Musical Note converter (Botros, 2001) and taken as the participant’s pitch ranking threshold for each frequency range. Where there were insufficient reversals due to the participant scoring consistently correctly at the smallest pitch difference (one semitone), the threshold for the purposes of this test was taken as the frequency at the one semitone difference as long as the participant had correctly pitch ranked two tones fifteen times in succession at this one semitone difference.

4.2.3.3 Vowel-Consonant-Vowel test

The VCV stimuli and procedure were identical to those used in the pilot study.

4.2.3.4 Institute of Hearing Research (IHR) sentence recognition test

Stimuli for the IHR sentences consisted of 16 lists of 15 sentences each. Sentences were of a simple subject – verb – object construction. Recordings of both a male and a female speaker of British English were available for each sentence. Speech-shaped background noise was overlaid on the sentence during playback. Signal to noise ratio altered throughout the task according to two interleaved staircases. Staircase 1 tracked the SNR for 33% correct answers (0 correct key words task became easier, 1 correct key word task remained at same level, and the task was made more difficult with 2 or 3 correct). Staircase 2 tracked SNR for 66% correct answers (0 or 1 correct makes it easier, stays at same level with 2 correct, more difficult with 3 correct).

Participants listened to sentences through headphones, and repeated what they heard as best as possible. Thirty sentences with a female speaker and thirty with a male speaker were presented. The test was scored using three key words – usually the subject, verb and object of the sentence – which were the targets for repetition.

4.3 Results

4.3.1 Chord Discrimination Test

Each participant's total percentage score for each test was converted to a d' score using the tables of Hacker and Ratcliff (1979). A multifactorial repeated measures ANOVAs were performed on the d-prime scores for the chord tests to determine the effects of the following factors: Tone (Piano Simulation, Sinusoid), Presentation Mode (Simultaneous, Sequenital), Chord Change (Middle note, Top note), Chord Root (C4, C5, C6, C7), and Semitone Difference (One, two, three). A between subjects factor of Device Model (MED-EL, Cochlear, AB) was also tested in this analysis. Each of the main effects from the analysis will be reported under a separate heading and the interactions reported at the end.

4.3.1.1 Factor: Tone (Piano Simulation, Sinusoid)

There was no significant main effect of the Tone factor ($F^{(1,15)} = 3.83$, $p = 0.07$). Figure 4.1 shows the similar distributions of the scores for the two tones conditions.

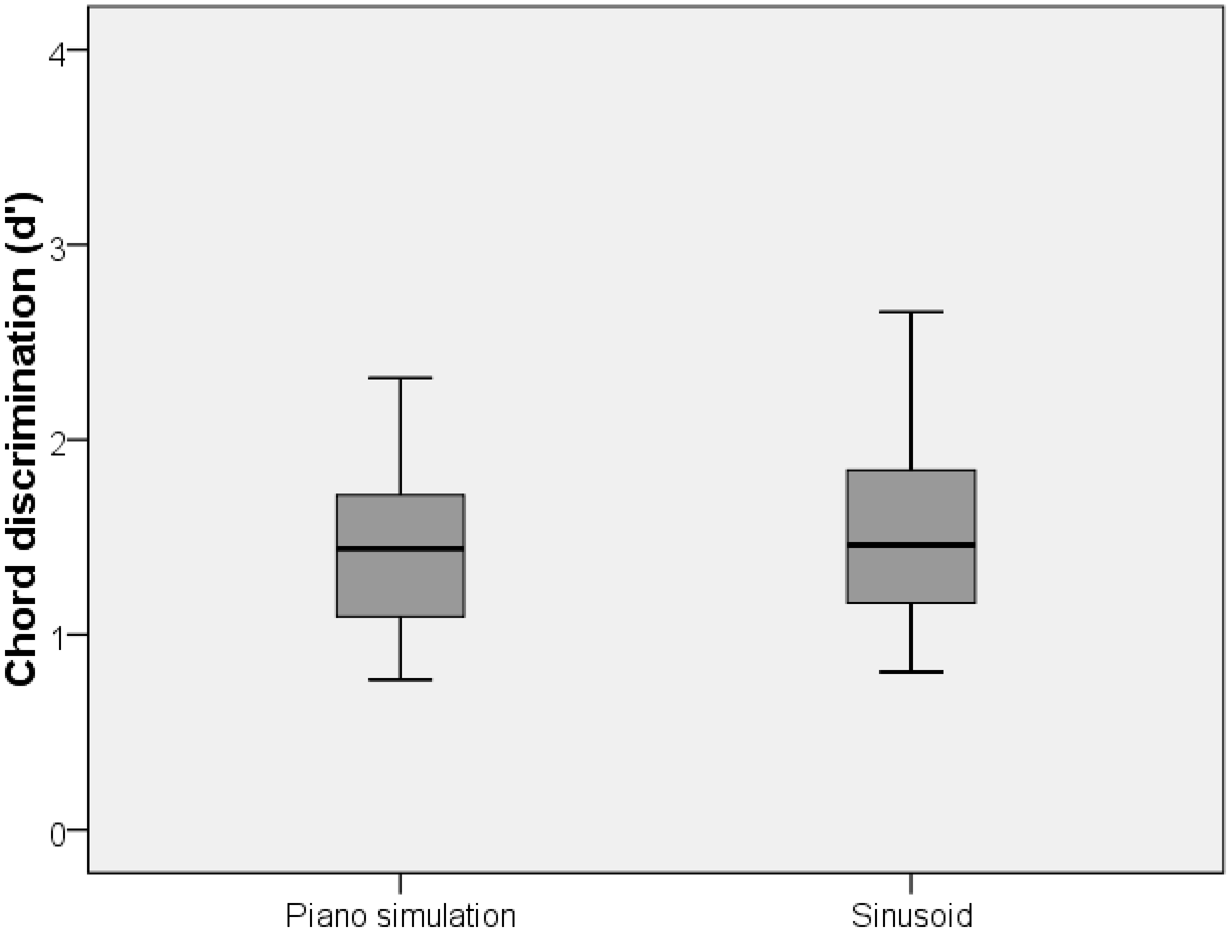


Figure 4.1: Boxplot of the distributions of scores (d') for the two Tone conditions. Dark horizontal lines represent the median, with the box representing the 25th to 75th percentiles, the whiskers the minimum and maximum values. Maximum possible d' score for a 2AFC task is 3.29, minimum is -3.29 (Hacker & Ratcliff, 1979).

4.3.1.2 Factor: Presentation Mode (Simultaneous, Sequential)

There was a near significant main effect of Presentation Mode ($F^{(1,15)} = 4.52$, $p = 0.051$). Figure 4.2 shows that the distribution of d' scores is broader for the Simultaneous condition than for the Sequential, but the medians are similar.

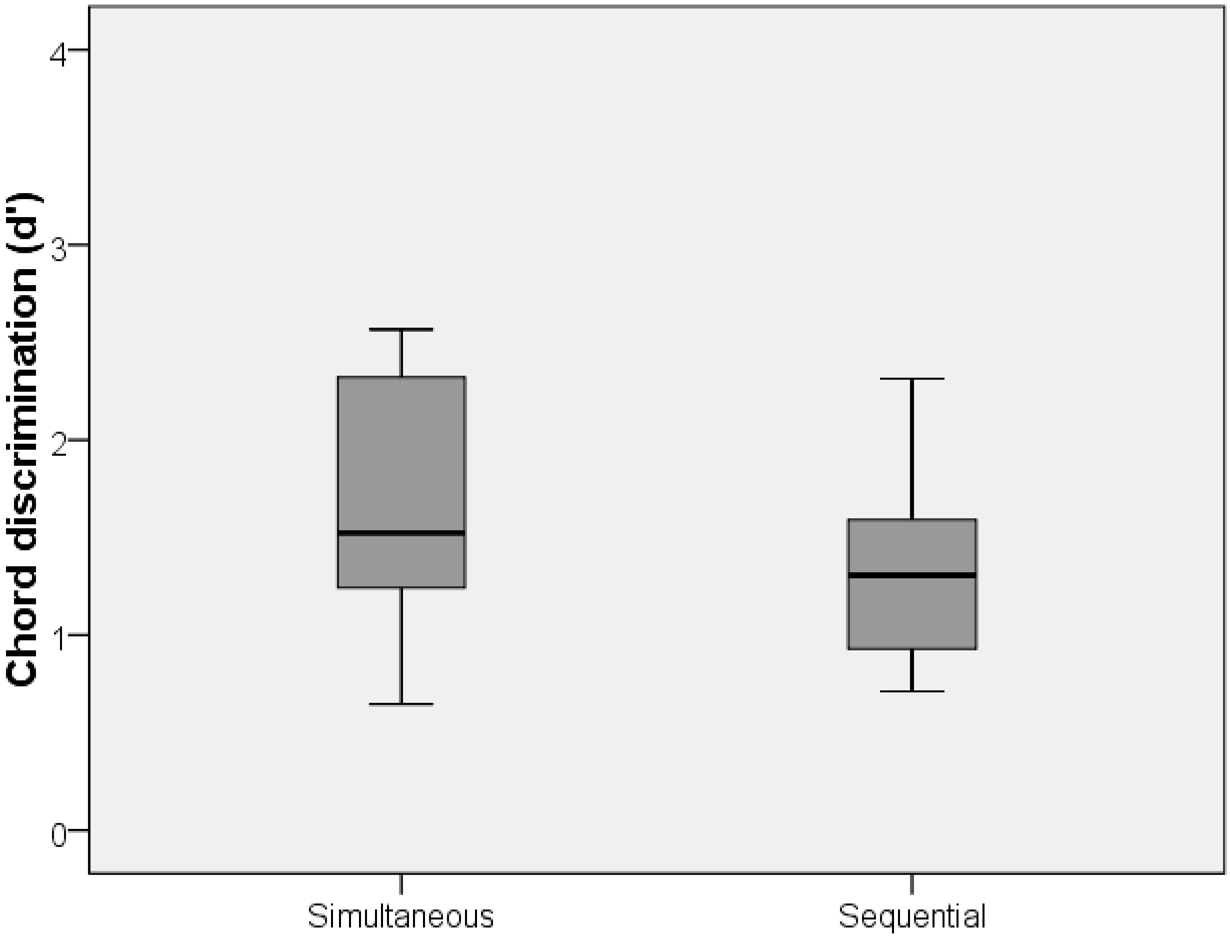


Figure 4.2: Boxplot of the distributions of scores (d') for the two Presentation Mode conditions.

4.3.1.3 Factor: Chord Change (Middle Note, Top Note)

There was a significant main effect of the Chord Change factor ($F^{(1,15)} = 14.96$, $p = 0.002$). Figure 4.3 shows that the median of d' scores was higher for participants identifying the Top Note rather than the Middle Note chord.

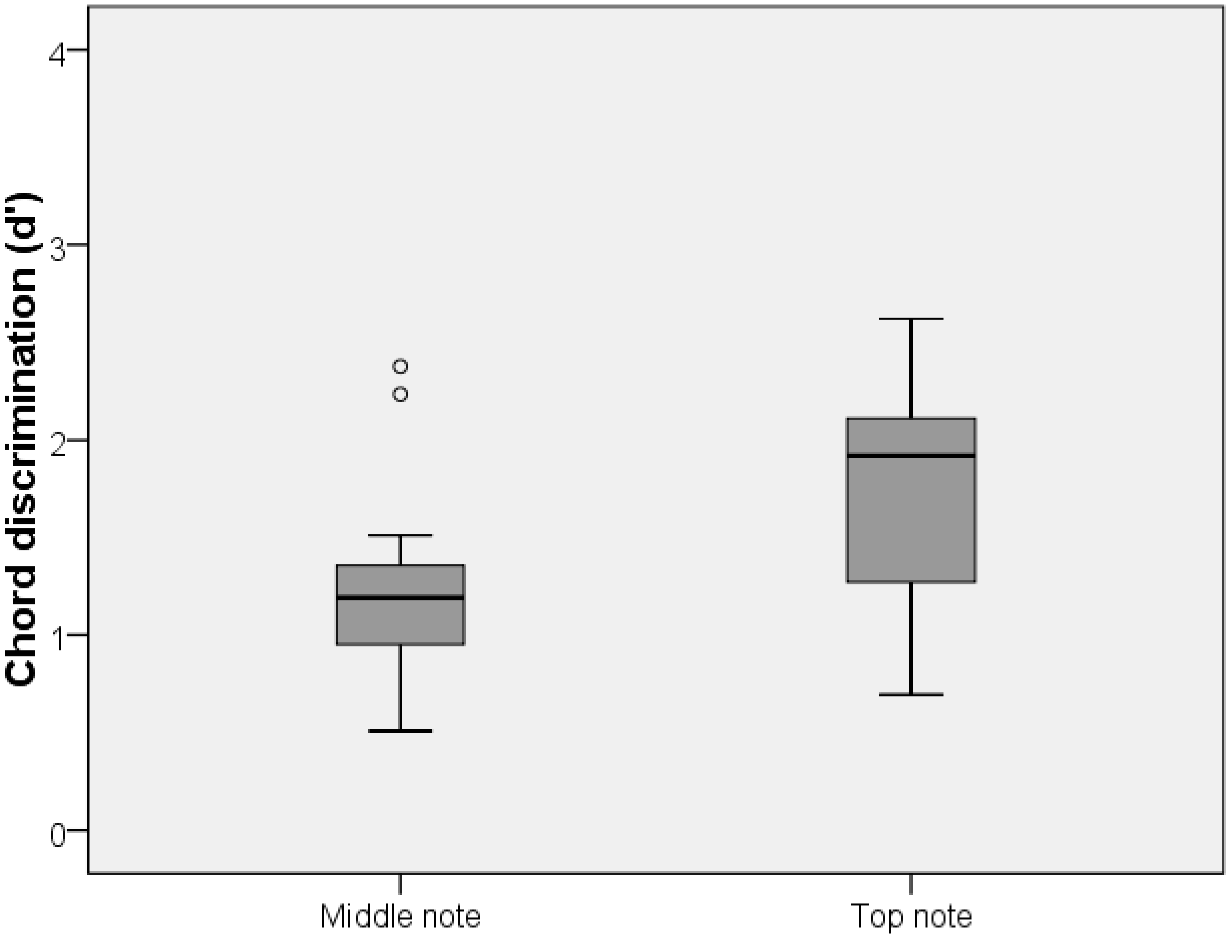


Figure 4.3: Boxplot of the distributions of scores (d') for the two Chord Change conditions. Circles represent outliers.

4.3.1.4 Factor: Chord Root (C4, C5, C6, C7)

There was a significant main effect of the Chord Root factor ($F^{(3,45)} = 4.67$, $p = 0.006$). Figure 4.4 shows the distribution of d' scores for chords with each of the four root notes. It can be seen that of the highest median score was for C5 and the lowest was for C7. Post-hoc tests were conducted using a Least Significant Difference test, and showed that significance in this factor was accounted for by a significant difference between the C5 and C7 frequency ranges ($p < 0.001$) and between the C6 and C7 frequency ranges ($p = 0.003$).

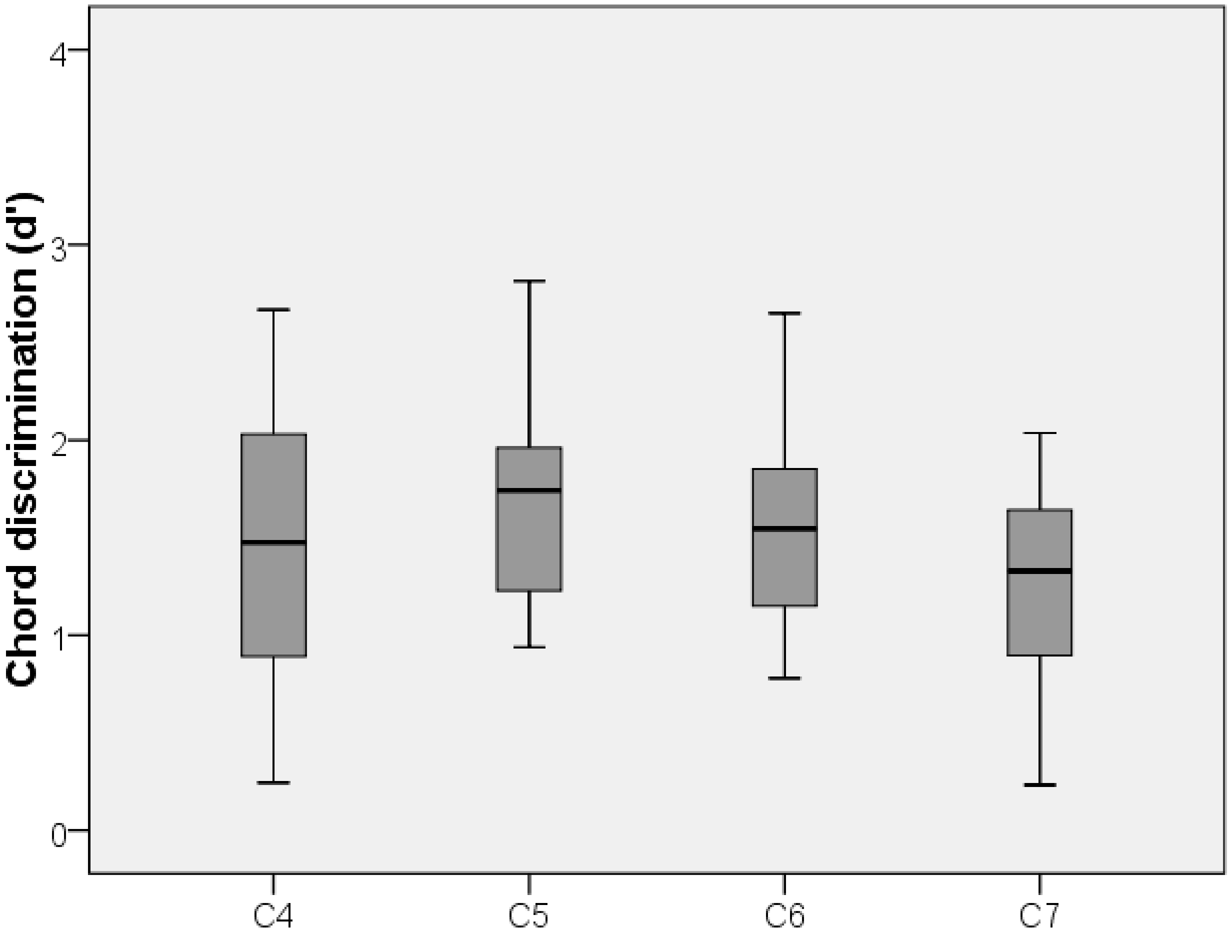


Figure 4.4: Boxplot of the distributions of scores (d') for the four Chord Root conditions.

4.3.1.5 Factor: Semitone Difference (One, two, three)

There was a significant main effect of Semitone Difference ($F^{(2,14)} = 153.25$, $p < 0.001$). Figure 4.5 shows the distribution of scores for the three conditions. It can be seen that median scores are much lower for the one semitone condition than for the two and three semitones conditions. Post-hoc tests were conducted using a Least Significant Difference test, and showed that all three Semitone Difference conditions were significantly different from each other at the $p < 0.001$ level.

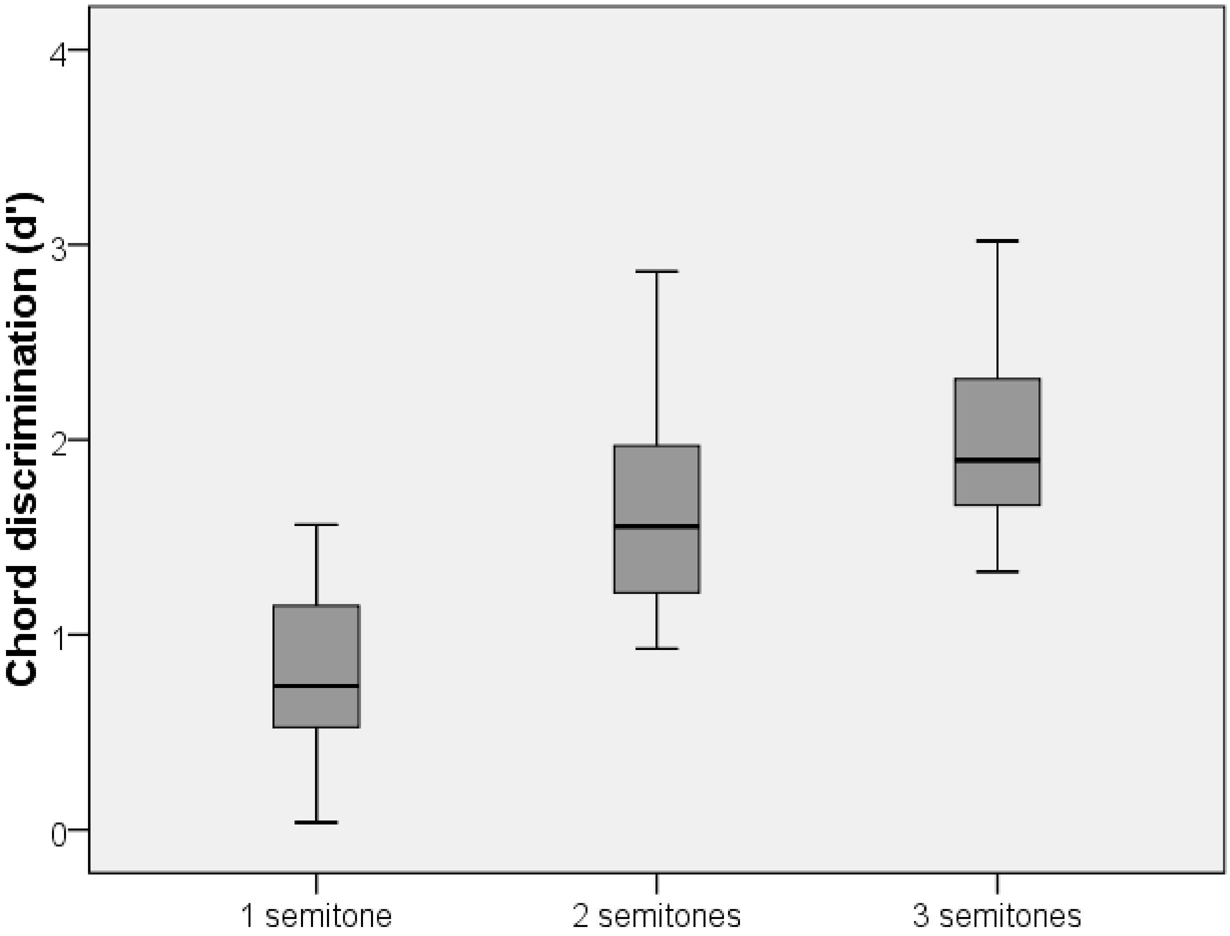


Figure 4.5: Boxplot of the distributions of scores (d') for the three Semitone Difference conditions.

4.3.1.6: Between Subjects Factor: Device model

Test of Between Subjects Effects show a significant effect of device ($F^{(2,15)} = 5.09$, $p = 0.02$). Distribution of scores for each device is shown in figure 4.6. Higher scores were achieved by participants with MED-EL devices, followed by Cochlear then AB.

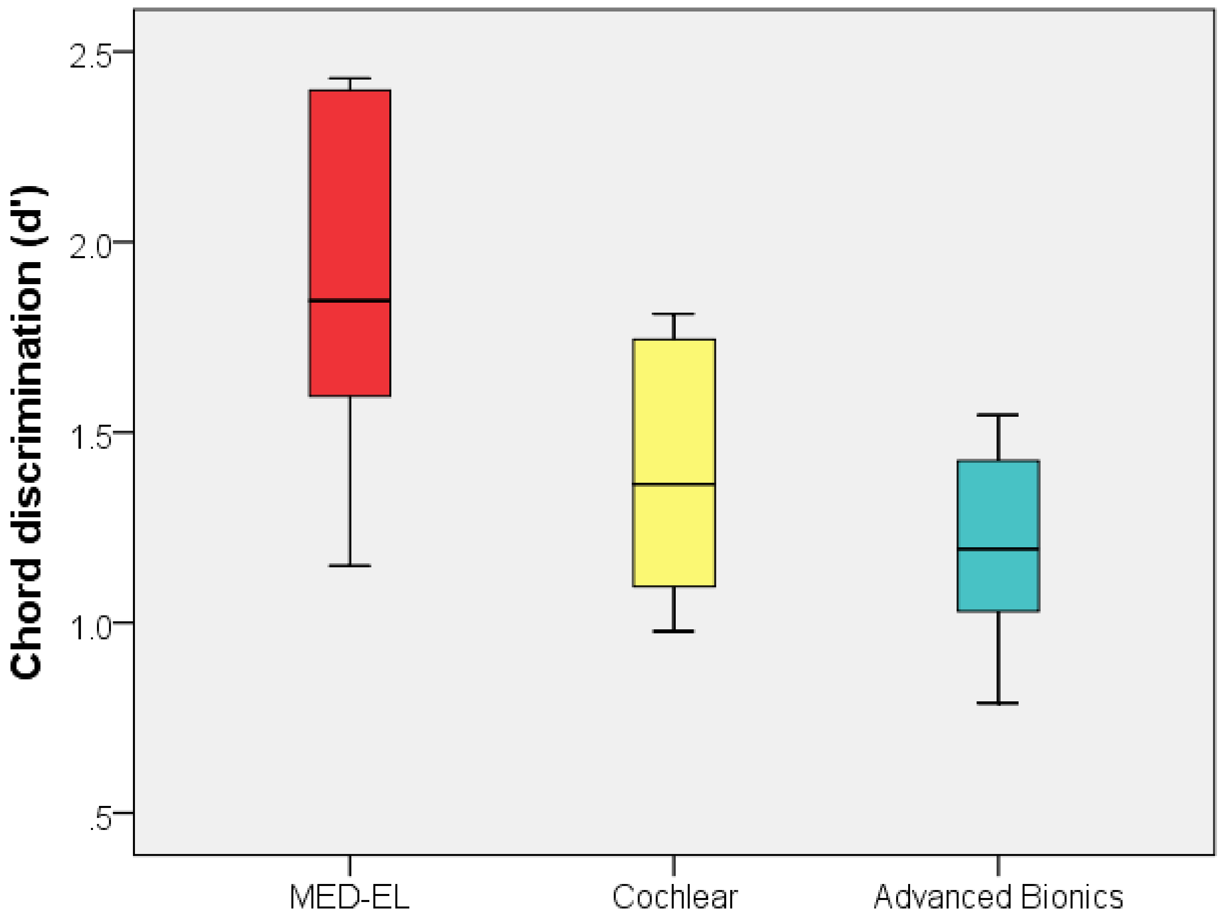


Figure 4.6: Boxplot of the distributions of scores (d'), separated by Device.

4.3.1.7 Interactions

There was a significant interaction between the Tone and Chord Root conditions ($F^{(3,13)}$ = 5.3, p = 0.003). The relative distributions of these two factors are shown in figure 4.7. This shows that, for lower frequencies (root notes C4 and C5), the median scores are similar regardless of tone. However, for the higher frequency (C6 and C7), median scores are much higher for the Sinusoid condition than for Piano Tone.

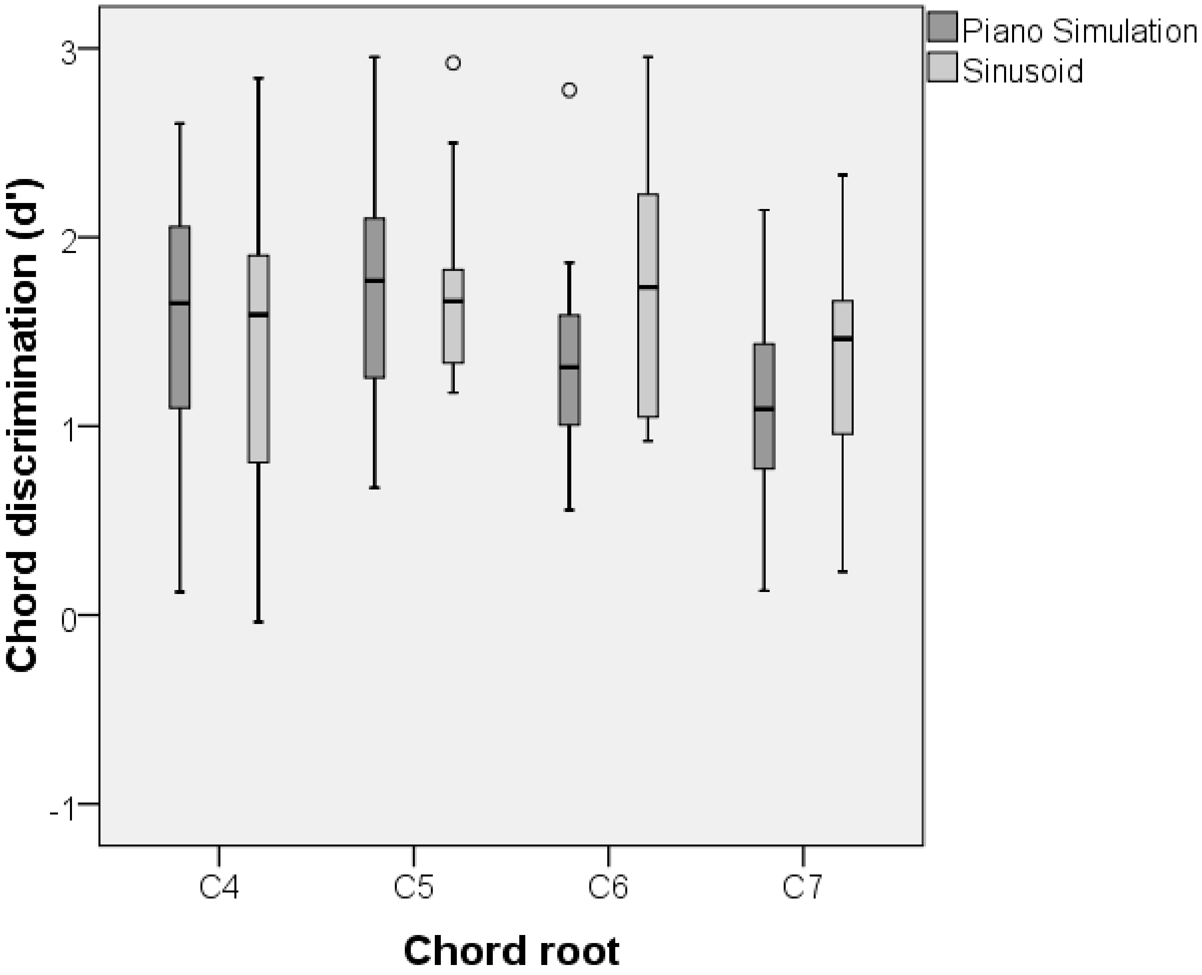


Figure 4.7: Distribution of the scores (d') for the four Chord Roots, separated by Tone. Circles represent outliers.

There was also a significant interaction between Tone and Presentation ($F^{(1,15)}$ = 5.46, p = 0.034). The relative distributions of these two factors are shown in figure 4.8. This shows the in the Simultaneous condition, median scores are slightly higher for Sinusoid stimuli, whereas for the Sequential condition, median scores are slightly higher for Piano Simulation stimuli.

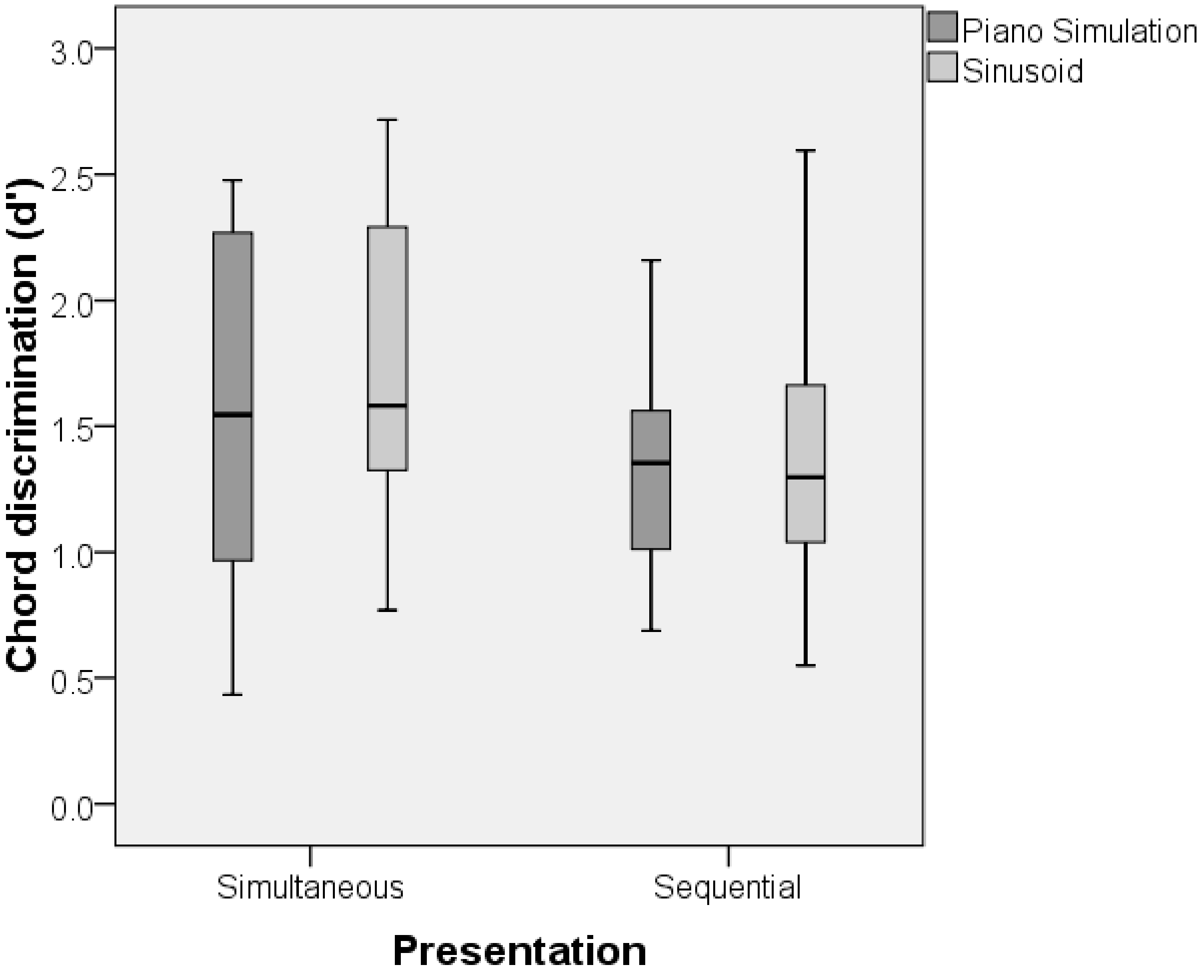


Figure 4.8: Distribution of the scores (d') for the Presentation factor, separated by Tone.

There was a significant interaction between Presentation and Device ($F^{(2,15)}$ = 4.31, p =0.03). Figure 4.9 shows that when the scores are separated by device, the difference between the means for the two presentation is distinct. MED-EL and Cochlear users perform better in the simultaneous condition, while for Advanced Bionics users the reverse is true.

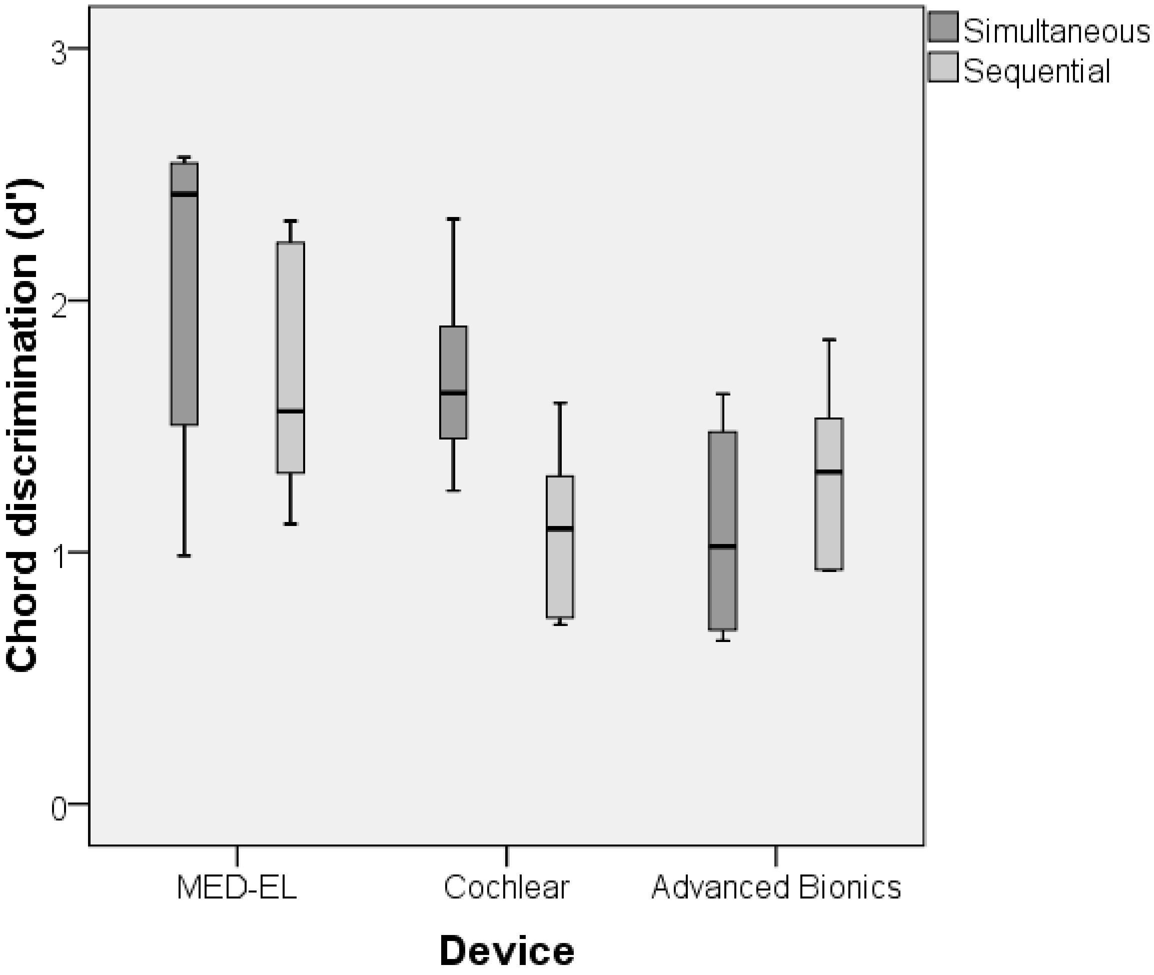


Figure 4.9: Distribution of d' scores for simultaneous versus sequential presentation, separated by device.

4.3.1.8 Comparison between pre- and post-lingually deafened participants on the Chord Discrimination Test

An independent samples t-test was run between the overall scores on the chord test with pre- and post-lingually deafened participants as separate groups. There was a significant difference between the two groups (t = -2.5, df = 16, p = 0.02). Figure 4.10 shows that post-lingually deafened participants performed better on the chord test than pre-lingually deafened participants.

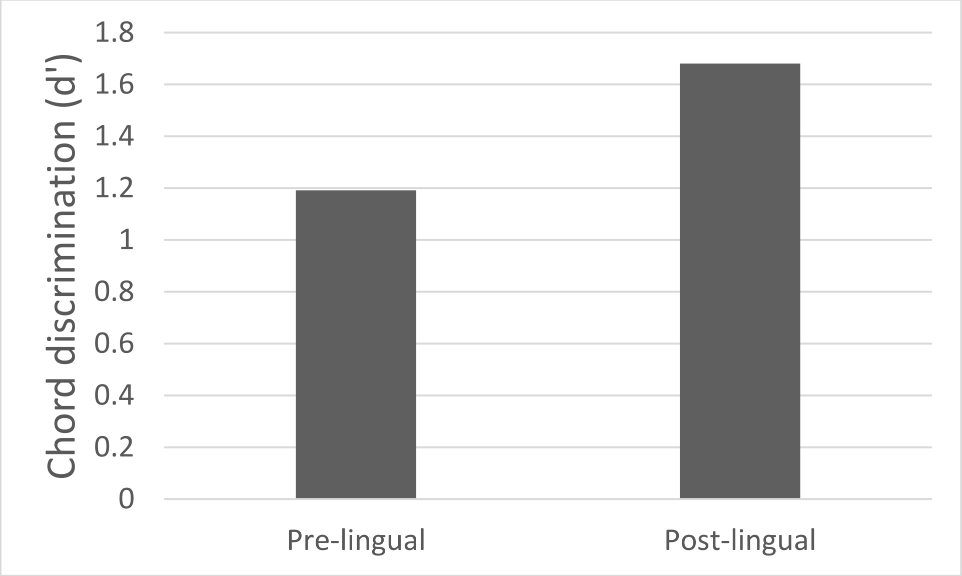


Figure 4.10: Average overall scores (d’) on the Chord Discrimination Test, separated by pre-lingually and post-lingually deafened participants.

4.3.1.9 Performance on the Chord Discrimination Test and questionnaire responses

Twelve participants who took part in this study also responded to the questionnaire study described in chapter 2. Figure 4.11 shows the average d’ score on the Chord Discrimination Test for these participants compared with their reported amount of time spent listening to music. Figure 4.12 shows these participants’ average d’ score on the Chord Discrimination Test compared to their reported enjoyment of music. It can be seen that the highest scores were achieved by those who reported both moderate amounts of time spent listening to music and moderate enjoyment of music.

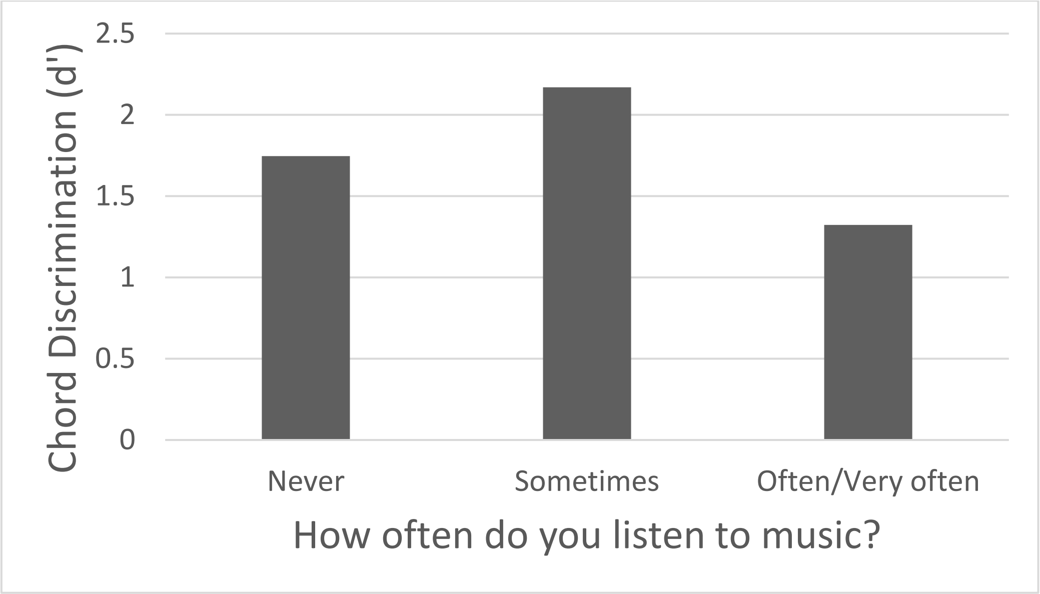


Figure 4.11: Average d' score on the Chord Discrimination Test for participants who carried out the questionnaire in chapter 2, compared with their reported amount of time spent listening to music

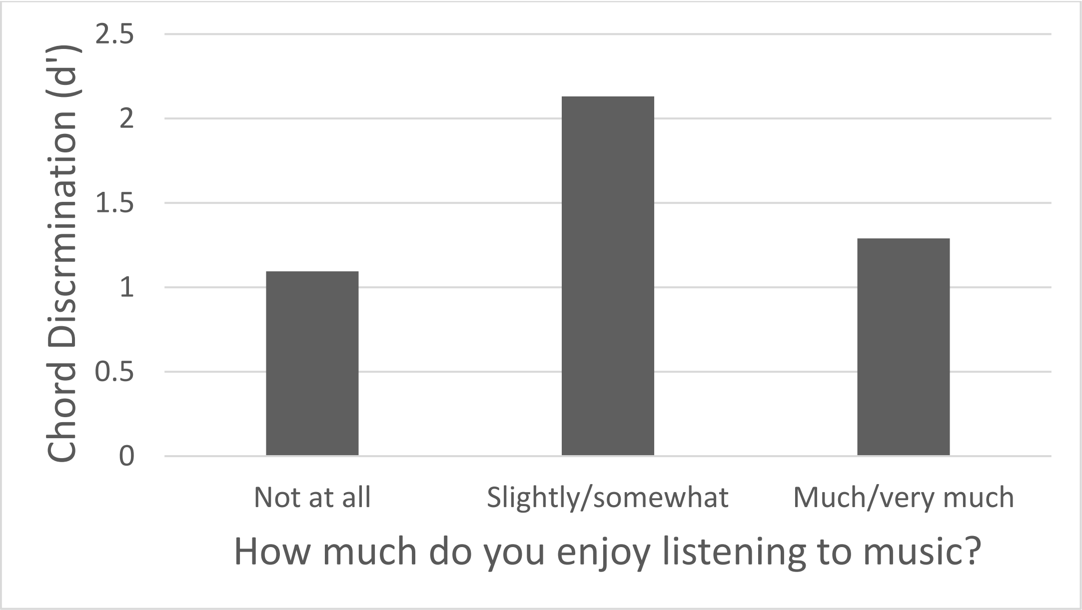


Figure 4.12: Average d' score on the Chord Discrimination Test for participants who carried out the questionnaire in chapter 2, compared to their reported enjoyment of music.

4.3.2 Adaptive Pitch Ranking Test

There was a great deal of individual variation in the results of the Adaptive Pitch Ranking test, with several participants consistently able to pitch rank at one semitone. Figure 4.13 shows the difference limens for each participant at each of the four reference notes (F♯4, F♯5. F♯6. F♯7). Figure 4.14 shows the median difference limens above the reference note, and figure 4.15 below the reference note, separate by device manufacturer. In general, participants with AB devices had higher semitone difference limens on this test.

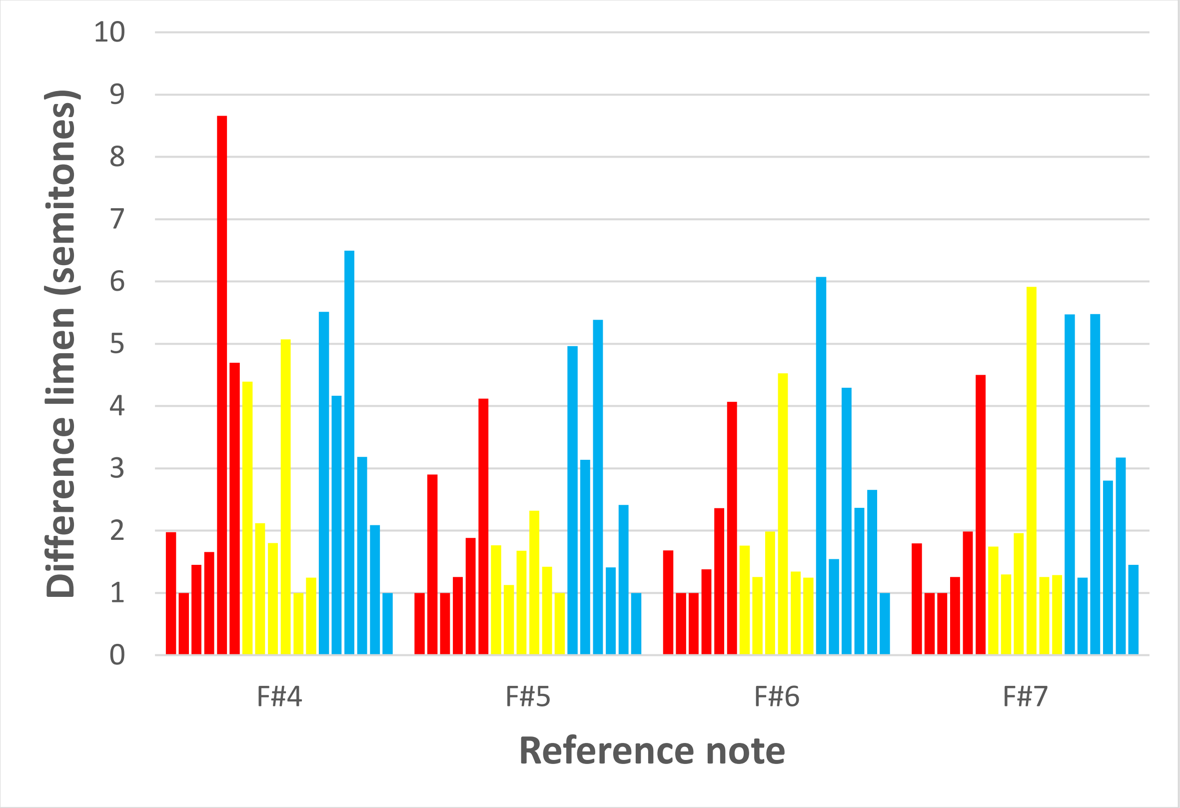


Figure 4.13: Difference limen in semitones for the 18 participants at the four reference notes. Red lines denote a MED-EL participant, yellow lines denote Cochlear participants and blue lines AB participants.

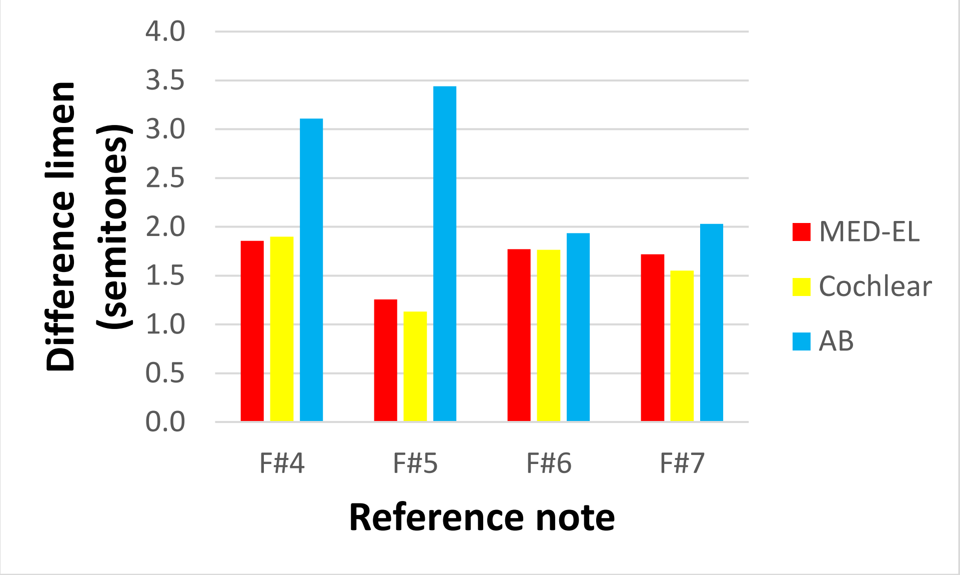


Figure 4.14: Median difference limen in semitones above the reference note separated by device manufacturer.

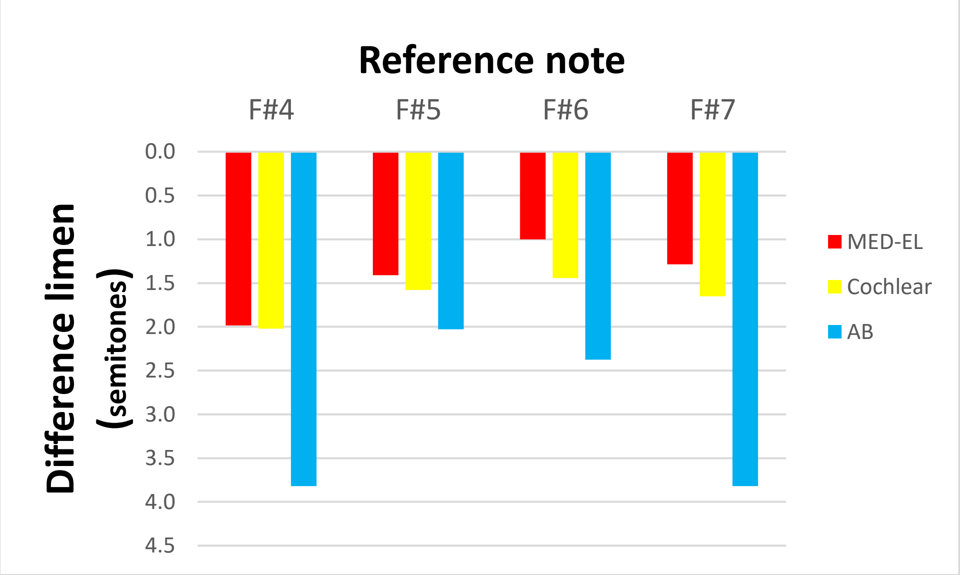


Figure 4.15: Median difference limen in semitones below the reference note separated by device manufacturer.

Results for the Adaptive Pitch Discrimination Test showed a positive skew. Therefore, correlations were carried out using Spearman's Rank Correlation Coefficient. There were significant correlations between Chord Test scores and semitone difference limens on the Adaptive Pitch Discrimination Test in every octave range, showing a moderate negative relationship. Correlation coefficients and significance levels are shown in table 4.4, and scatterplots of these correlations are shown in figures 4.16, 4.17, 4.18 and 4.19..

Table 4.4 Correlation coefficients and values of p for the correlations between the Chord Test scores and average semitone difference limens for the four octave ranges.

Octave range	C4	C5	C6	C7
Correlation Coefficient	-0.512	-0.513	-0.588	-0.492
Value of p	.03	.029	.01	.038

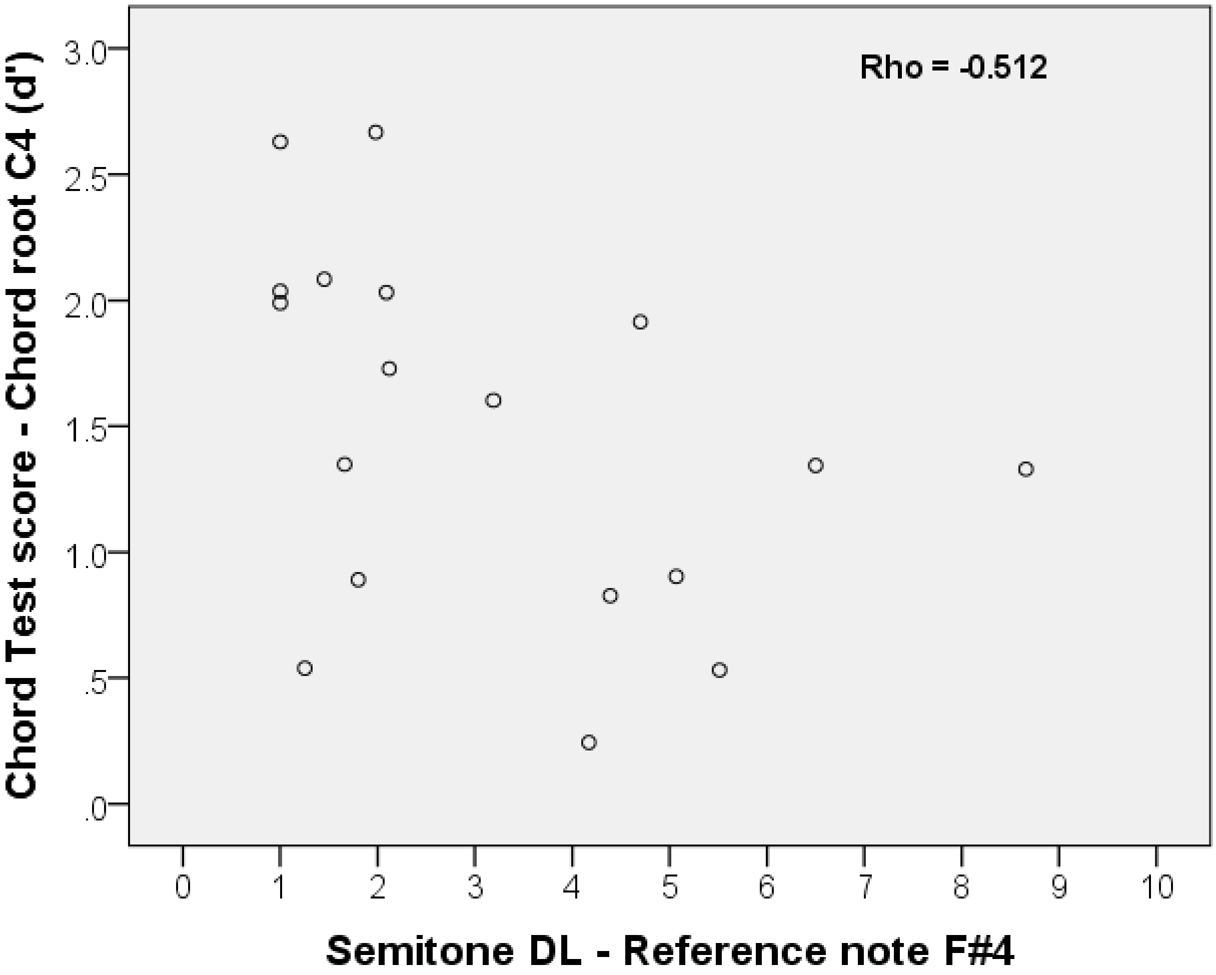


Figure 4.16: Scatterplot of the correlation between Chord test scores (d') and the Semitone Difference Limens for the Adaptive Pitch Ranking Test in the C4 octave

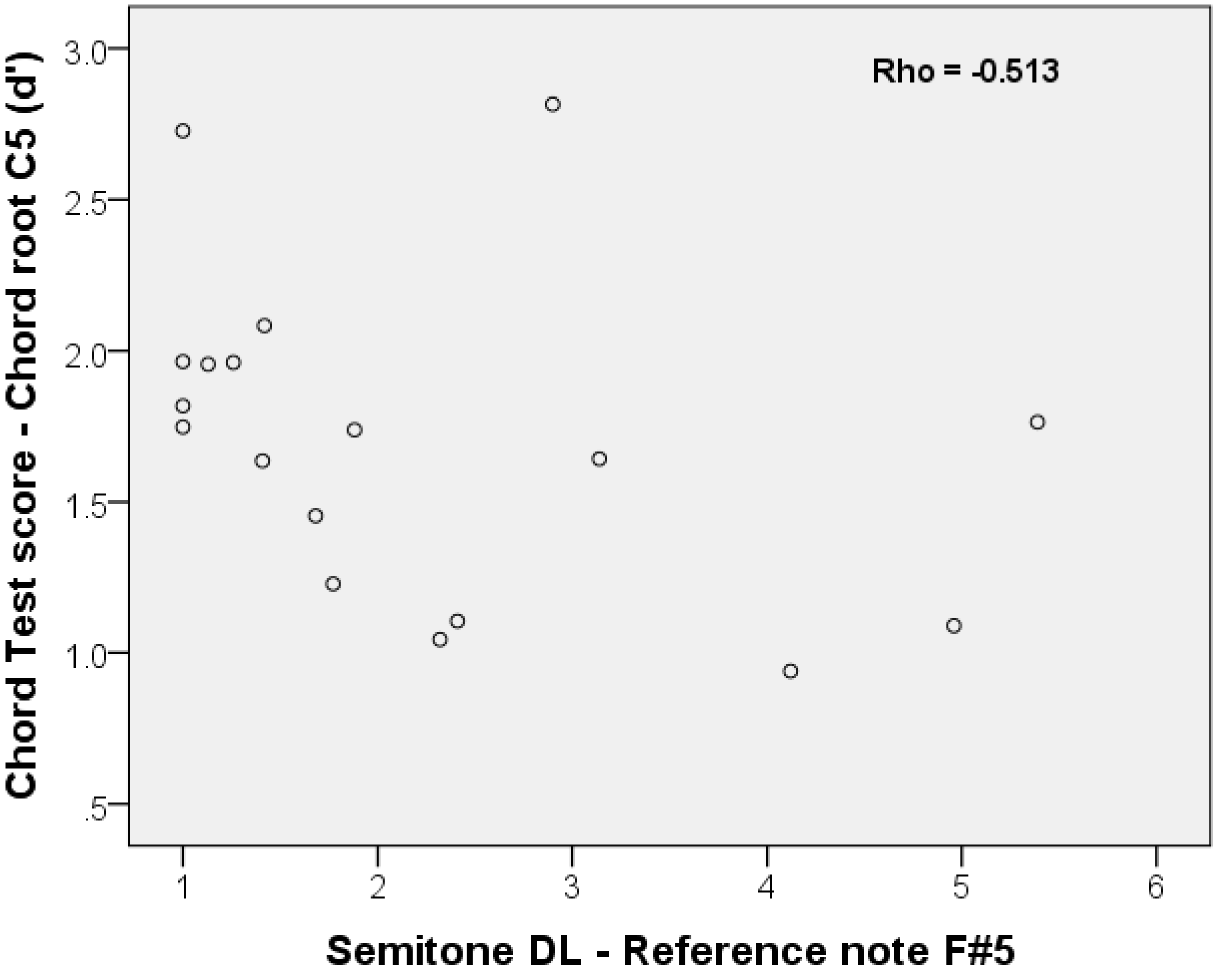


Figure 4.17: Scatterplot of the correlation between Chord test scores (d') and the Semitone Difference Limens for the Adaptive Pitch Ranking Test in the C5 octave.

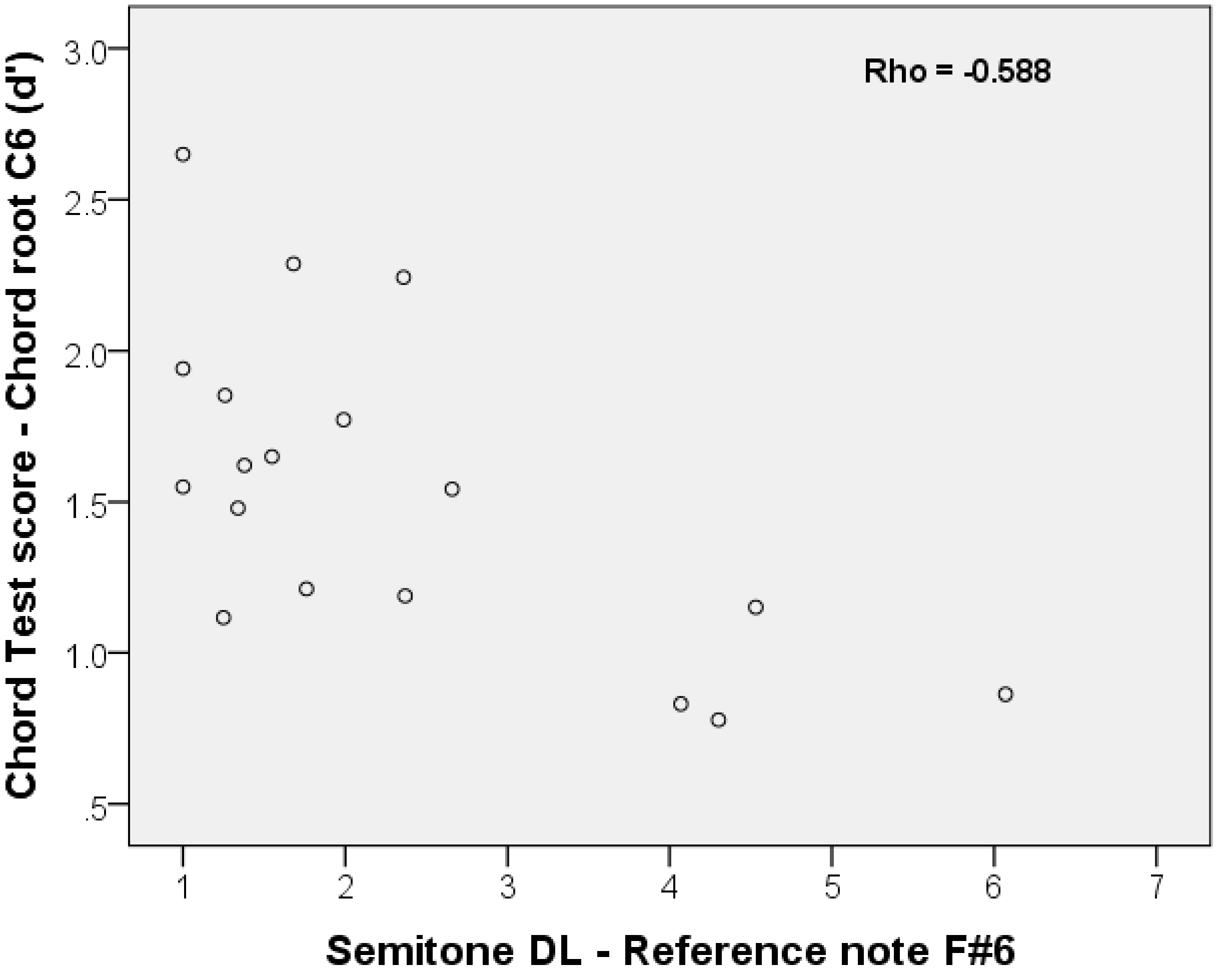


Figure 4.18: Scatterplot of the correlation between Chord test scores (d') and the Semitone Difference Limens for the Adaptive Pitch Ranking Test in the C6 octave.

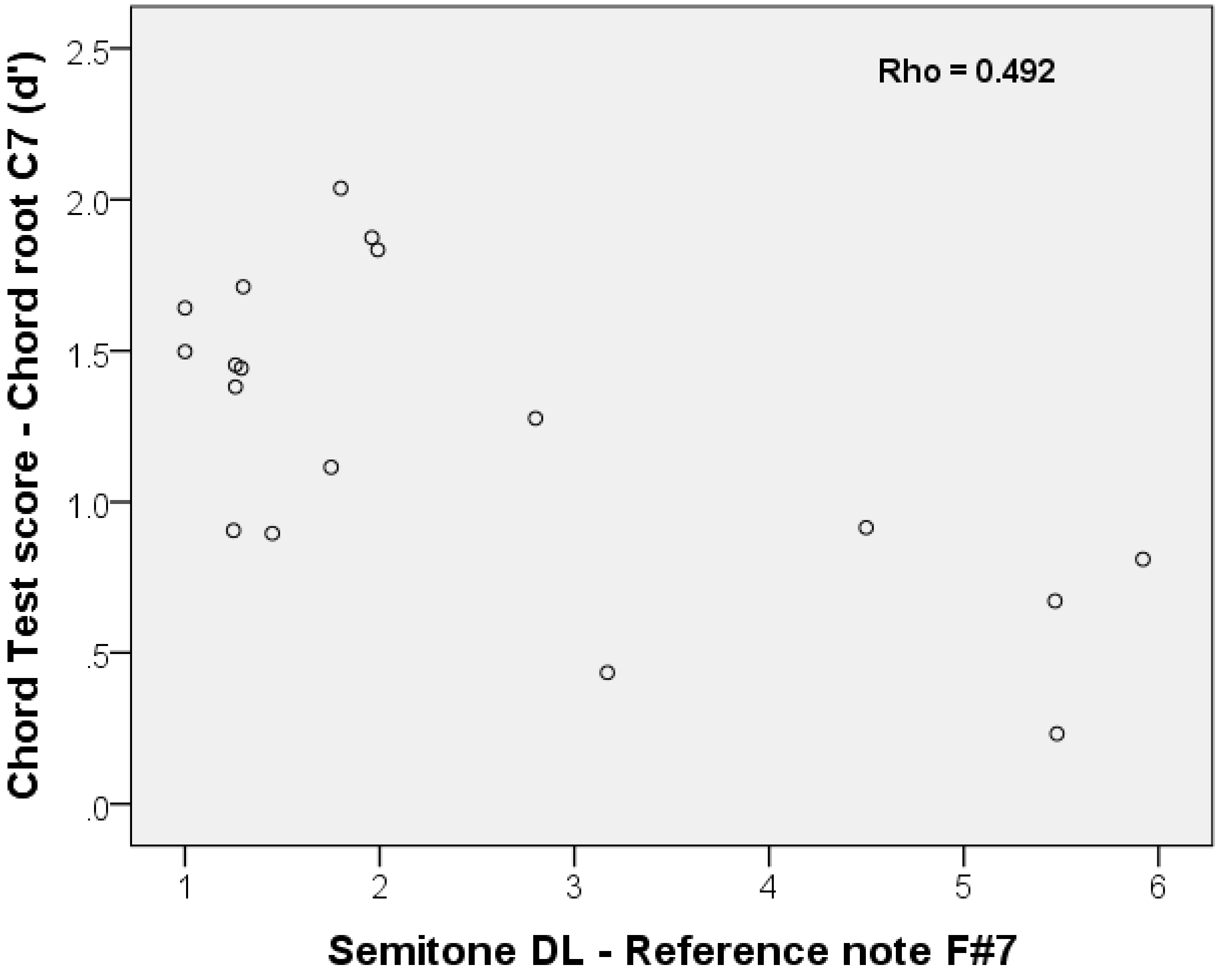


Figure 4.19: Scatterplot of the correlation between Chord test scores (d') and the Semitone Difference Limens for the Adaptive Pitch Ranking Test in the C7 octave.

4.3.3 Vowel-Consonant-Vowel test

VCV percentage correct scores were converted to d prime scores according to Hacker & Ratcliff (1979). Individual performance of each participant on correctly identifying the voicing, manner and place of the consonants, as well as overall correct answers, is shown in figure 4.20. Performance on the three consonant features as well as overall correct answers separated by device model is shown in figure 4.21.

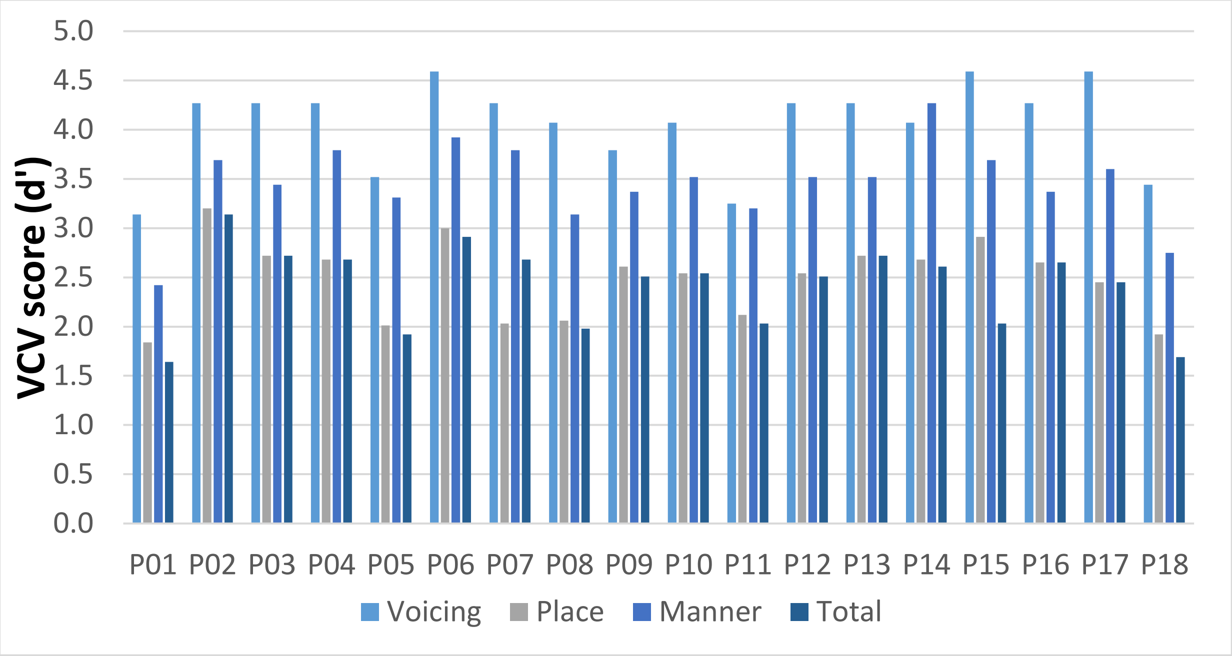


Figure 4.20: Individual correct consonant identification (d') for 18 participants

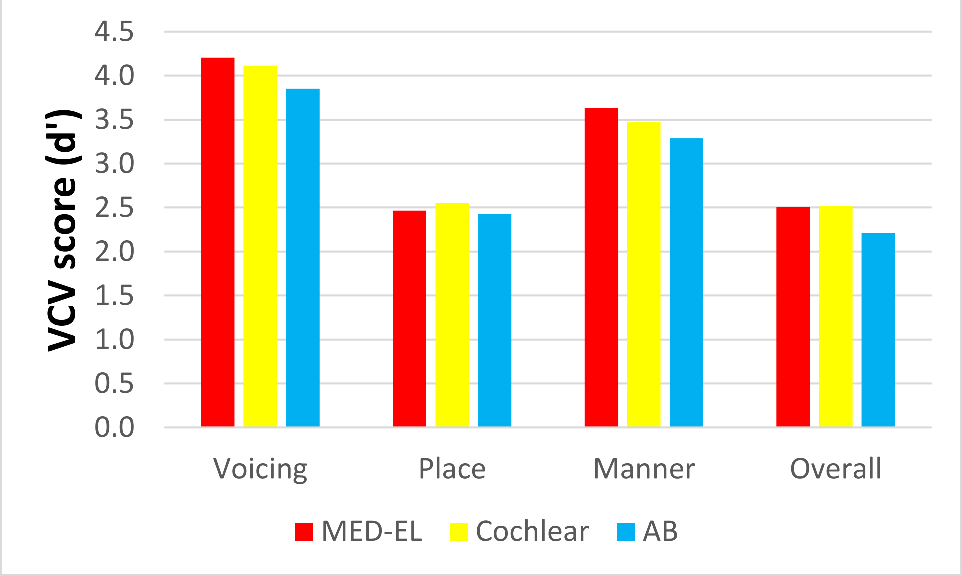


Figure 4.21: Performance on voicing, manner, and place as well as overall consonant recognition, separated by device model.

The VCV data showed a negative skew, therefore, non-parametric statistical methods were used. A Spearman correlation analysis was carried out between Chord test and VCV test d prime scores to detect any dependence between participants' abilities on their chord test with speech recognition skills. There was a significant correlation between VCV scores and chord scores using Piano Simulation tones (rho = 0.58, p = 0.01) but not Sinusoid tones (rho = 0.45, p = 0.06). A scatterplot of the two correlations can be seen in figures 4.22 and 4.23

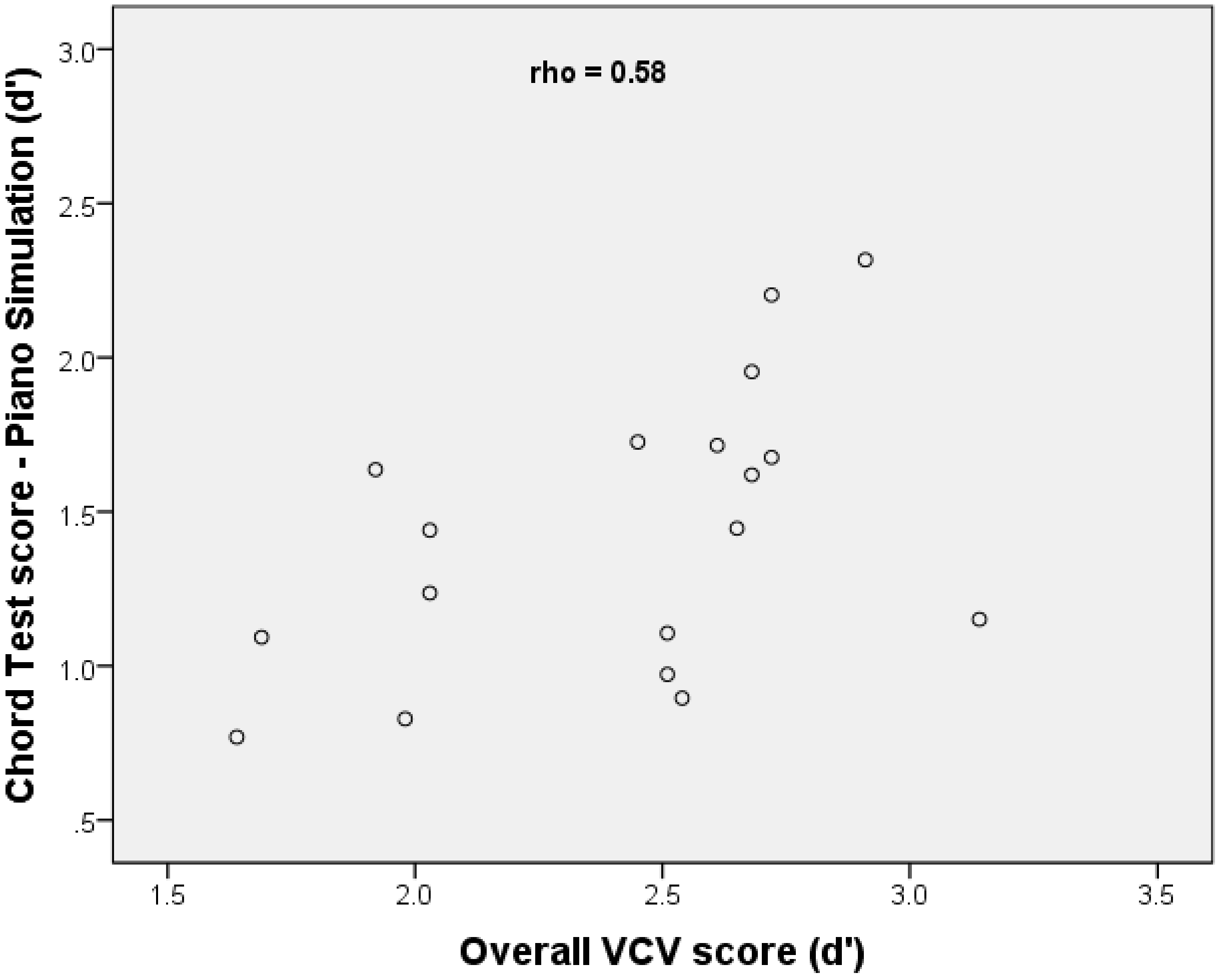


Figure 4.22: Scatterplot of the significant correlation between the d' scores for the Piano Simulation condition of the chord test, and the overall VCV scores.

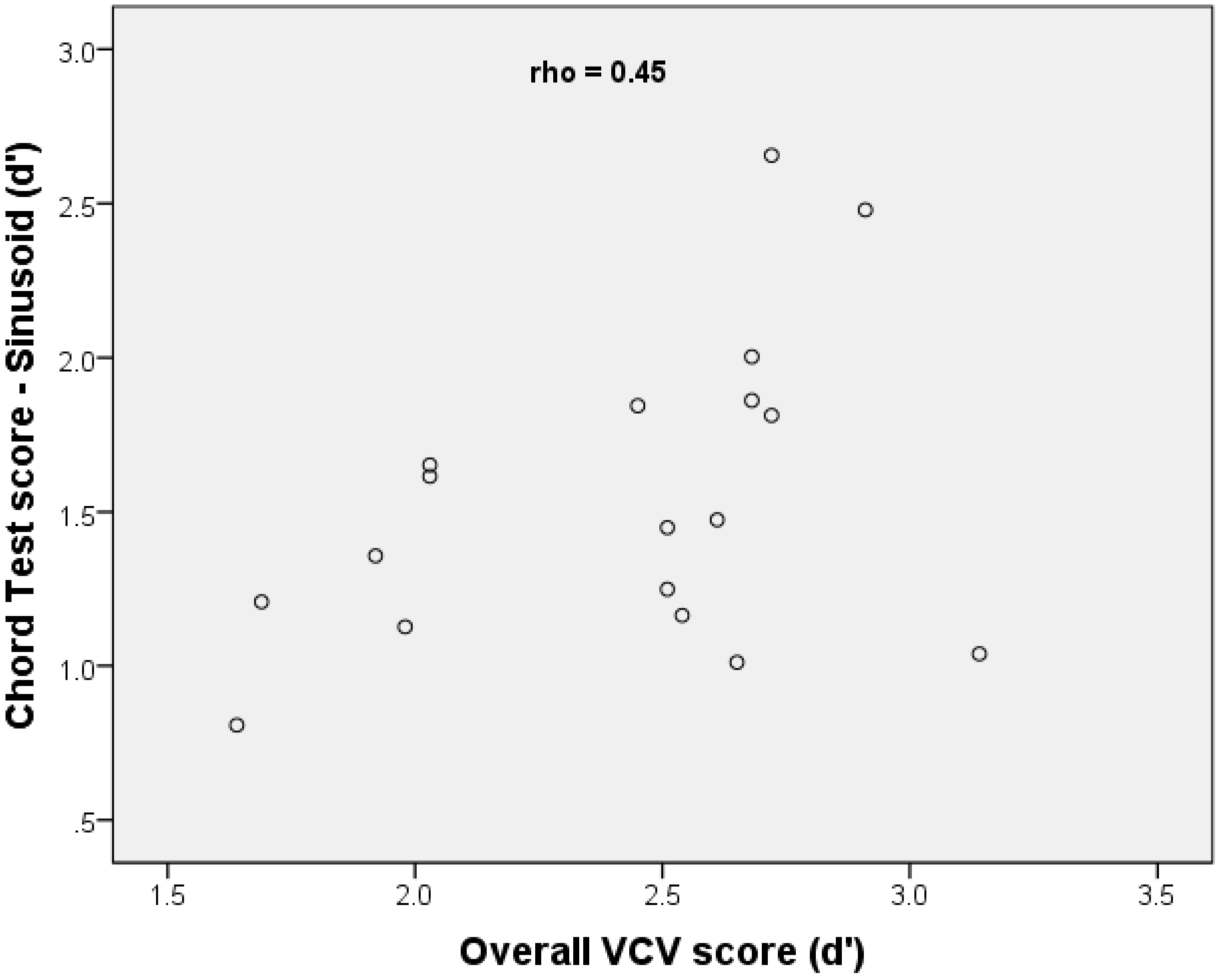


Figure 4.23: Scatterplot of the non-significant correlation between the d' scores for the Sinusoid condition of the chord test, and the overall VCV scores.

Spearman correlation analysis between VCV scores and scores on the four Chord Root conditions in the Chord Discrimination Test showed a significant correlation between VCV scores and scores for the C5 Chord Root condition (rho = 0.74, $p < 0.001$) but no significant correlations with the other Chord Roots, as shown in table 4.5.

Table 4.5: Correlation coefficients and values of p for the Spearman correlation analysis run between VCV scores and the four Chord Root conditions of the chord test. A significant correlation is highlighted.

Chord Root	**C4**	**C5**	**C6**	**C7**
Correlation coefficient	0.40	0.74	0.43	0.37
Value of p	0.10	<0.001	0.07	0.13

4.3.4 IHR sentence recognition test

The IHR sentence test yielded four scores for each participant at each run:

1. Average SNR at 33% correct, female speaker
2. Average SNR at 33% correct, male speaker
3. Average SNR at 66% correct, female speaker
4. Average SNR at 66% correct, male speaker

Scores for the first and second run of each task were run through a Pearson correlation, and found to be highly correlated. Additionally, t-tests showed no significant difference between the two runs. Pearson correlation coefficients, t-test statistics and values of p for all calculations are shown in table 4.6. Therefore, an average score across both runs was calculated. Figure 4.24 shows the average SNR at reversals at 33% and 66% correct when listening to female and male speakers for all 18 participants, and figure 4.25 shows the results separated by device model. In these figures, lower scores represent better speech in noise recognition.

Table 4.6: Pearson correlation coefficient and value of p, and t tests statistic and value of p, for the two runs of the IHR sentences in noise test.

Gender of speaker	Percent correct level	Pearson correlation		T test	
		Correlation coefficient	Value of p	Test statistic	Value of p
Female	33	0.79	0.001	0.06	0.95
Male	33	0.74	0.002	0.71	0.49
Female	66	0.76	0.002	1.09	0.29
Male	66	0.63	0.012	1.5	0.16

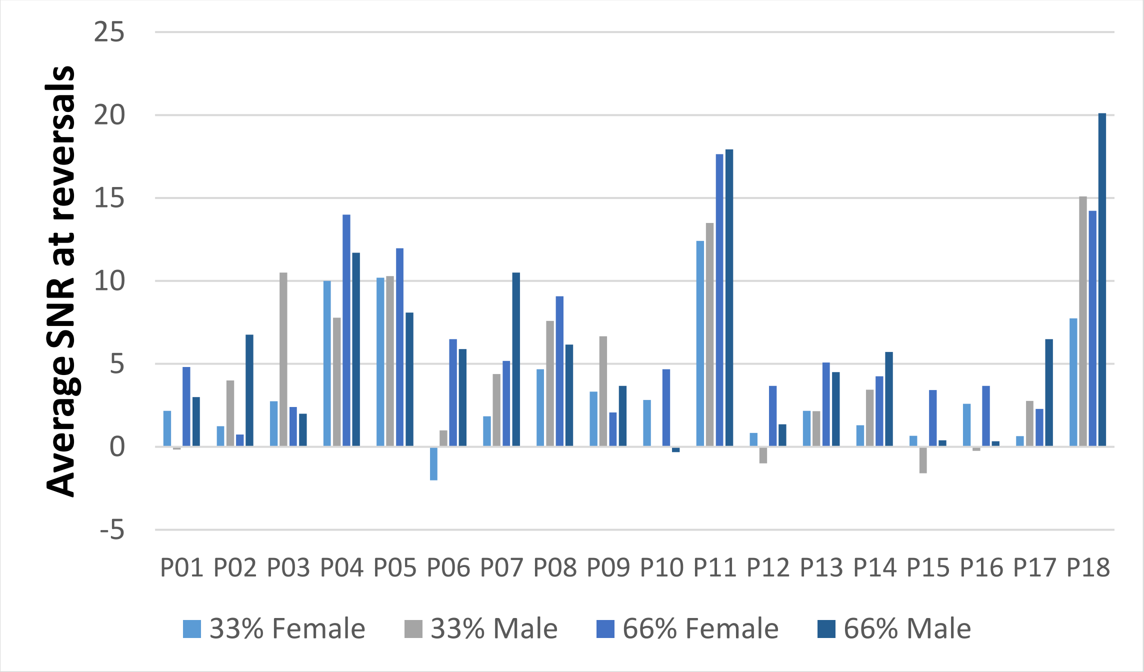


Figure 4.24: Average SNR at 33% and 66% correct when listening to female and male speakers for 18 participants

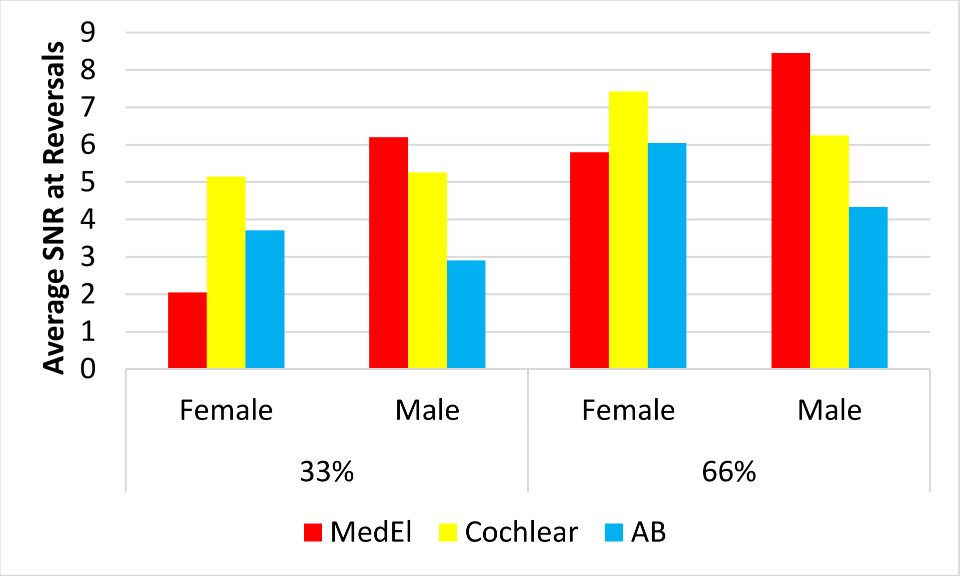


Figure 4.25: Average SNR at 33% and 66% correct when listening to female and male speakers for 18 participants, separated by device model

There were no significant correlations between the IHR sentence test results and any of the overall scores on the music or pitch perception tests.

4.4 Discussion

In this study, pitch perception in musical contexts for CI users was further examined using musical chords. The task used in this study was a further development of the task in the pilot study described in chapter 3, looking at the impact of pure tones versus complex tones, and the relationship between music perception and speech perception for CI users.

Stimuli in the modified Chord Discrimination Test were complex tones simulating a piano tone, as well as sinusoid tones. Complex tones were used because CI users are more commonly exposed to complex stimuli in everyday life, so it was more representative of the individual's general level of pitch perception. The prediction for this aspect of the experiment was that it would be more difficult to perform the task with complex stimuli than sinusoids (Gfeller et al., 2002; Sucher & McDermott, 2007, Singh et al., 2009). In the present study, no significant difference in performance was found between the two tone category conditions (Piano Simulation versus Sinusoid). This finding does however concur with the results obtained by Donnelly et al. (2009). In their study CI and NH listeners were asked to identify whether stimuli consisted of one, two or three simultaneous tones. The stimuli were made up either of pure tones or piano tones, and no significant difference in performance was seen between the two groups of stimuli, with participants able to carry out the task in either condition. There was, however, an interaction between the Tone factor and the Chord Root factor. This showed that it was easier for participants to recognise the difference between the chords made up of Sinusoid stimuli at higher frequencies, with root notes C6 and C7. This corresponds to frequencies above 1 kHz. This is in keeping with previous findings that in tasks using pure tones, higher frequencies may be easier than lower frequencies (Smith et al., 2009). Singh et al. (2009) also found that melodies comprised of pure tones were easier for CI users to recognise than melodies comprised of complex tones at higher frequencies.

In the pilot study of the Chord Discrimination Test, there was a significantly better performance on chord in the Simultaneous condition than Sequential It was hypothesized that this could be related to auditory memory, with the sequential stimuli being harder to remember over the course of the task due to their length. Unlike in the pilot study, the difference between scores in the present study was not significant based upon whether the notes of the chord were presented simultaneously or sequentially (although it did approach significance). There was however an interaction between the Tone and Presentation factors, with a performance slightly better for the Sinusoid tones than the Piano Simulation in the Simultaneous condition, and the reverse being true in the Sequential condition. This conflicts with research done by Singh et al. (2009), who found that pure tone melodies were easier for CI users to recognise that those made up of complex tones.

There was a significant effect of Chord Change, with participants performing better at identifying the change in chord when top note changes, rather than when the middle note of the chord is changed. The Top Note condition of the Chord Change factor corresponded to the Major-Augmented chord contrast in the pilot study, which was not found to be significantly different than the Major-Minor contrast. The present study altered this condition by the addition of two and three semitone changes on top of the one semitone change found in the Major-Augmented contrast. The fact that this factor became significant as a results of this change suggests that it cannot be explained either by the hierarchy of tones theory (Krumhansl & Cuddy, 2010), or be the tense nature of the augmented chord (Cook & Fujisawa, 2006), as both these explanations would have predicted a significant effect of the Chord Contrast factor in the pilot study as well as in the present study. The simplest explanation is therefore that the change of the top note of the chord may be perceptually more prominent, but the one semitone change used in the pilot study was too difficult for most CI users to discern. this is in keeping with previous studies. Huron (1989) conducted a study in which listeners were asked to identify the number of voices present when listening to a piece of music by J.S. Bach, and to state when the number changed. It was found that entries of outer voices (that is, notes higher or lower than those already being played) were easier to identify than entries of inner voices.

Comparisons between results on the Chord Discrimination Test and speech perception tests were carried out. The significant effect of the Chord Root factor, with scores peaking in the C5 region (covering 523 Hz – 988 Hz) is interesting to note alongside the correlation between overall scores for the C5 Chord Root and overall VCV scores. The C5 octave covers frequencies which correspond to the first formant of many spoken vowels, which is important for speech recognition (Catford, 2001). The higher scores in the C5 octave may therefore be a result of the focus on speech perception in CI sound processing strategies and rehabilitation. The significant correlation between scores on the VCV test and Chord Discrimination scores in the Piano Simulation tone condition. This could suggest that participants with better abilities with regards to perception of spectral information important for consonant recognition (Faulkner 2006; Donaldson & Kreft 2006) are able to use the same capabilities in recognising pitch changes in complex stimuli. An unexpected finding however was the scores on the IHR sentences in noise test did not correlate with any scores on the Chord Discrimination Test. Previous research has shown that speech in noise correlated to performance on pitch and music tasks for CI users (Gfeller et al., 2007), however, this study used spondees rather than sentences, which may be a more difficult task. Overall, however, the scores on the IHR test were very variable, with a great deal of individual difference, and other research has found the speech recognition is not a predictor of pitch perception (Gfeller et al., 2008).

Despite the complexity of the stimuli used in the Chord Discrimination Test, it was still within the capabilities of CI users to perform. The chord test battery used in this study expanded on the protocol of the pilot study, in which only pitch differences of one semitone were used. The present study also examined pitch discrimination where the chords differed by two or three semitones. There was a significant improvement with the increasing numbers of semitones in the Semitone Difference condition. This shows that the task of discerning small differences in musical chords and chord note sequences is within the capabilities of CI users, as it becomes easier with an increased interval – if the task were especially difficult in itself for CI users, a significant improvement would not be likely.

The results of this study indicated that a disparity exists in some CI users' abilities to perceive pitch differences depending on the context in which sounds are heard. In the adaptive pitch ranking test, where tones were heard in isolation, some participants were able to successfully rank the smallest difference (one semitone) with ease. It is likely that several participants would have been able to pitch rank at differences smaller than one semitone had such stimuli been included in the task. However, the one semitone limit was deemed sufficient for the present study, as it matched the lowest difference in the chord discrimination task. There was a moderate negative correlation between adaptive pitch ranking and chord test results in each octave range, but many participants who had difficulty in the chord test when the difference in the target chord was one semitone had no such problem when pitch ranking at one semitone, suggesting that pitch perception in a musical context presents a greater challenge than when listening to isolated pitches. This is in keeping with research by Pressnitzer et al. (2005), who found that CI users were unable to identify the changing note in the subsequent melody test, even when the change was greater than their previously determined pitch ranking thresholds. Other studies have shown that the complexity of the stimuli has a negative effect on CI users' ability to perceive changes in pitch (Gfeller et al., 2002; Sucher & McDermott, 2007, Singh et al., 2009).

Better performance on the Chord Discrimination Test was seen for CI users with MED-EL devices. However, it is important to consider some of the individual factors pertaining to this sample of CI users. In the pilot study, there was an approximately equal proportion of pre- and post-lingually deafened participants for each device. In the present study, the group of participants with AB implants included a much higher proportion of pre-lingually deafened adults than the users with MED-EL and Cochlear devices. Post-lingually deafened participants were shown to perform better on the Chord Discrimination Test. This might account for the relatively poor performance of AB users across many of the tests as the AB group of participants had the most pre-lingually deafened – three deaf from birth and one in childhood.

A significant finding of this study is the fact that a good performance on objective tests of music perception does not necessarily correspond to better enjoyment of music. Post-lingually deafened adults taking part in this study performed significantly better on the Chord Discrimination Test than the pre-lingually deafened participants. However, pre-lingually deafened participants were more likely to report enjoying music much or very much in the questionnaire study described in chapter two. Additionally, for participants of the present study who also completed the questionnaire, highest average scores on the Chord

Discrimination Test were seen for those who reported only moderate enjoyment of music and time spent listening. As discussed in chapter 2, a CI users' enjoyment of music may have more to do with personal factor than enjoyment of music. post-lingually deaf adults can negatively compare their experience of music with the CI with their previous NH music listening experience, which pre-lingually deaf CI users cannot do. This is supported by the fact that children with CIs, who also have no memory of music with normal hearing, are much more likely to report enjoyment of music than adults with CIs (Nakata et al., 2005; Hopyan et al., 2011). This finding suggests that looking at a CI user's background and hearing history may give more clues to their potential enjoyment of music than objective tests of pitch perception.

4.5 Limits of the test battery and future directions

A clear limitation of the test battery as developed and employed in this study was in designing the pitch ranking test to have a smallest pitch difference of one semitone. This was done for two reasons; firstly, as the focus of this research is on pitch perception in musical contexts, it was deemed appropriate for the test to be confined to the pitch intervals which are meaningful in a musical context; and secondly, keeping the smallest pitch change in the pitch ranking test as one semitone meant that it matched the smallest change in the chord test. However, this caused issues with the pitch ranking test which were only discovered once testing had begun, as participants who had lower FDLs were able to easily pitch rank at one semitone. Future implementations of the test battery should modify the pitch ranking task so as to include pitch difference of less than one semitone, which would allow for an easier comparison between performance on the pitch ranking test and on the Chord Discrimination Test. This raises the question of including pitch differences smaller than one semitone in the chord test itself. This possibility will be explored further in chapter 5.

4.6 Summary of findings

1. There was no significant difference between results on the Chord Test using complex stimuli and sinusoid stimuli; however at higher frequencies, better results were achieved with pure tone stimuli.

2. Unlike in the pilot study, there was no significant main effect of Presentation seen. The significant interaction between Tone and Presentation suggests this may be caused by the inclusion of complex tones.

3. The change of the top note of the chord was easier to detect than a change in the middle note.

4. Peak performance occurred in the C5 octave range, which also correlated with scores on the VCV test, suggesting a relationship between speech and music perception in this frequency area.

5. Chord differences were easier to perceive as the semitone difference between the chords increased.

6. Device related factors were difficult to conclude due to individual differences amongst the participants.

7. The complexity of the musical context may make it more difficult to perceive small pitch changes.

8. Post-lingually deafened participants performed significantly better than pre-lingually deafened participants, but better performance does not necessarily correspond to better enjoyment of music.

Chapter 5 – Assessing pitch perception in musical chords in hearing impaired and normally hearing children

5.1 Introduction

The studies reported in chapters 3 and 4 have shown that the Chord Discrimination Test can be used to assess pitch perception in a musical context in adults with CIs. However, it is not known if such tests can be used to evaluate pitch perception in children with CIs. CI surgery for children was first introduced in the mid-1980s, and today, the majority of profoundly deaf children in the UK use a CI, with approximately 350 children born each year with sufficient hearing impairment to make them eligible for a CI. There is a small cohort of young adult CI users who were implanted as children; however, currently the majority of adults with CIs will have been implanted following the development of language, with many implanted following a long stretch of their life being lived as a hearing person. In contrast, children with CIs who were pre-lingually implanted have no experience of sound beyond what their CI has delivered, and will not have any experience of music perception with a NH auditory system with which to compare their CI experience. Their sound and pitch perception have developed through electrical hearing which is very different to most adults with CIs.

5.1.1 Pitch and music perception in NH and HI children

In NH children, the ability to understand and process pitch differences begins at a very early developmental stage. Processing of sounds in the cochlea begins at around 20 weeks' gestation, and the structure of the cochlea is fully formed at 25 weeks. This allows the foetus to start learning skills associated with the perception of pitch even before birth (Bibas et al., 2008). In the prenatal and neonatal phase, infants are able to differentiate between an unknown female voice and that of their mother (Kuhl et al., 1992). Development of the ability to recognize changes in pitch and melody occurs early on in infancy (Carral et al., 2005; Plantinga & Trainor, 2009). Pitch perception abilities approach that of adults by around the age of six or seven. Trehub et al. (1986) tested infants and young children on their ability to detect a semitone difference in melody sequence of five notes. Both groups were able to detect the semitone change, with the older group performing better when the notes were presented in the context of a diatonic scale. Performance on tasks relating to pitch perception has been shown to improve both with age and with experience of music (Lamont, 1998).

HI children who use CIs can achieve good speech and language skills, especially with early implantation (Miyamoto et al., 1999). As there is greater cortical plasticity in the brain of a growing child than in that of an adult, it may enable them to adapt better to electronic hearing then an adult (Nakata et al., 2005). A great deal of research into CI users' performance on pitch-related tasks, such as pitch ranking and pitch discrimination, has been carried out with adults, but fewer studies have been done with child CI users. Perception of pitch is difficult for CI users because much of the temporal pitch detail (rapid fluctuations in stimulus) is not conveyed for frequencies above 200 to 300 Hz due to the processing approach used within CIs. This has a negative impact on melody and voice pitch perception. In CI processing, only the temporal envelope is delivered, and the faster temporal fluctuations above about 300Hz are discarded (Zeng, 2002; Schauwers et al, 2012). Because of this, spectral location (or place) information is the most apparent pitch cue for a CI user, but this is also limited by the number and placement of the electrodes on the implanted electrode array.

There is some evidence that HI children perform better than HI adults at pitch perception tasks. Looi (2014) looked at the results of four studies using the same pitch ranking task to compare pitch perception abilities of CI and HA using adults and children. The task was a two alternative forced choice pitch ranking task using intervals of one, half, and a quarter octave (12, 6 or 3 semitones). The stimuli were sung /a/ vowels. Results showed that both the children using CIs and those using HAs performed significantly better than adults with CIs.

Despite this, children using CIs are outperformed by NH children on pitch related tasks. Looi and Radford (2011) carried out a pitch ranking task with four groups of children: CI users, children with bimodal stimulation (both a CI and a HA), HA users, and NH children. As in the review mentioned above (Looi, 2014), stimuli for the task were sung /a/ vowels, and the intervals to be ranked were twelve, six or three semitones. The NH group of children scored significantly higher than the CI group on ranking all three intervals. The HA group was also significantly better than the CI group at ranking twelve and six semitones. However, the CI group did perform better than adult CI users undertaking the same test in previous studies. A similar result was reported in the study by Edwards (2013), who assessed the pitch perception and musical and singing abilities of NH children as well as children using CIs, HAs and bimodal stimulation. Pitch perception was assessed with a task in which the children identified whether two sequences of musical notes were the same or different. Children with CIs were outperformed not just by the NH children, but also the children using HAs and bimodal stimulation.

These deficits in pitch perception have an impact on the performance of children with CIs in musical tasks, such as recognising songs and melodies, and identifying emotions in music. Several studies have been carried out looking at abilities of children with CIs to recognise familiar melodies. In one such study, children with CIs aged 4 to 9 were presented with theme songs from popular television programs. The children were asked to identify the TV show that corresponded to each song, and children also gave ratings of how much they liked each song. Trials were carried out first with the songs presented to the children in blocks. The children first listened to the original version of the theme song, followed by an instrumental (karaoke) version with vocals removed, and finally a version which preserved only a synthesised flute version of the main sung melody. Children performed significantly better at identifying the original version than the instrumental or melody-only version. These results suggest that the lyrics and the familiar instrumental accompaniment were important factors to the success of children's identification of the songs. The pitch and timing information included in the melody only version was not enough for identification, lacking the other specific cues to the song, such as instrumentation and lyrics. However, ability to identify the songs did not impact on the children’s ability to enjoy the music, as they gave positive appraisals for all versions of the tunes (Nakata et al., 2005).

Another study used television theme songs to specifically look at the ability of children with CIs to use pitch information to recognise songs. This study, carried out by Volkova et al. (2014), involved eight bilateral CI users aged between 5 and 7, and sixteen NH children aged between 4 and 6, matched for 'hearing age' with the CI participants. Children were tasked to identify eight television theme songs with which they were familiar. The songs were presented in three different versions: melodic, which consisted of the main melody line played on a synthesised flute; timing-only, which preserved only the tempo, metre and rhythmic structure of the song; and pitch-only, which preserved the pitch intervals of successive tones but all tones were presented with equal duration. NH children were above chance on all three conditions. CI children matched the performance of the NH children on the melodic versions of the songs, but were slightly above chance for the timing-only condition and at chance for the pitch-only condition, at which they performed significantly worse than the NH children. The better performance on the melodic versions suggests that the children with CIs were able to make use of the pitch cues only when presented in combination with the timing cues; pitch cues alone were not enough to allow them to recognise the song.

The ability to recognize emotions in music is closely linked with pitch perception, as it is often very subtle pitch changes which dictate the emotional nature of a piece of music, as for example the semitone difference between a major and minor chord which causes it to sound happy or sad. Pitch perception deficits with CI hearing may also make it difficult for children with CIs to assign emotions to music. NH children are able to assign emotions to music as well as adults at age 11 (Hunter et al., 2011). A number of studies have used a musical emotion recognition task known as the Peretz test (Peretz et al., 1998) to examine musical emotion recognition in children with CIs. This tests consists of excerpts from classical compositions lasting between 7 and 33s, which participants listen to and identify whether they sounded happy or sad. These excerpts used mode (major or minor) and tempo (fast or slow) to distinguish between happy or sad examples. Major keys and fast tempos are perceived as happy, while minor keys and slow tempos are perceived as sad (Hevner, 1935; Peretz et al., 1998).

Hopyan et al. (2011) carried out a study using the Peretz test with NH and children with CIs. Though exceeding chance, the children with CIs were significantly less accurate at identifying the emotion of the music than the NH children. Shirvani et al. (2014) tested 25 children with unilateral CIs and 30 NH children also using the Peretz test. The scores of children with CIs were significantly lower than NH children, with overall scores of 56% compared to NH children's 91%. This is in keeping with findings that children with CIs also have difficulty discerning the emotional content of speech, which can denoted by changes in voice pitch (Hopyan-Misakyan et al., 2009, Chatterjee et al., 2015). Despite this, CI children were more likely than adults to report enjoying listening to music.

These studies have shown that, despite outperforming adults with CIs, children with CIs are at a disadvantage compared to their NH peers when it comes to the perception of pitch-related aspects of music. Despite this, some studies have shown that children with CIs are more likely to report enjoyment of music than adults with CIs (Nakata et al., 2005; Shirvani et al., 2014). Given their enjoyment of music despite difficulties compared to NH children, pitch perception is an important focus for research in children with CIs. One potential way of developing the pitch perception capabilities of children using CIs is through music related training programmes.

5.1.2 Musical training programmes

A number of studies have been carried out to ascertain whether training in musical activities may improve the pitch perception abilities of children with CIs. Chen et al. (2010) tested 27 children with CIs using a two alternative same-different forced choice task comprising piano tones ranging from 256 Hz (approximately C4) to 495 Hz (approximately B4). Thirteen of the children had received structured musical training either before or after implantation. The difference between the two notes ranged from 0 to 11 semitones, and the tones could appear in ascending or descending pitch order. Where the two notes were correctly identified as different, the child would then have to identify whether the second tone was higher or lower than the first. The duration of training positively correlated with scores on overall and ascending pitch interval perception. Separating the children by age showed that this correlation was accounted for by children under the age of 6, although children over 6 scored significantly better on the pitch perception task, suggesting that younger children had the most potential to benefit from the training programme

Di Nardo et al. (2015) carried out a study looking at the effects of music training on the ability to identify songs in children with CIs. Their Music Training Software involved a test in which participants listened to two piano notes falling between C4 and C7, and state if they were the same or different. Children practiced with this test for at least two hours a week. At the beginning and end of training, an adaptive pitch discrimination test, and a music test were administered. In the music test, children were first trained to identify each of five melodies with a related cartoon character. Following this, they were presented with either a full instrumental or a melody only version of each song, and had to identify the cartoon character related to that song. Ten children aged 5 to 12 years took part. Prior to training, the smallest frequency discrimination achieved by any of the children was 4 semitones, but following the training, 8 of the ten children could discriminate to one or two semitones. There was also a significant improvement on the song identification test.

These studies have shown that training in musical activities may improve the pitch perception abilities of children with CIs. The present study examines the effects of a singing training programme on the pitch and speech perception of children using CIs and HAs as well as NH children.

5.1.3 The present study

In the study described in this chapter, the Chord Discrimination Test was piloted in a paediatric version with a group of children who were taking part in a singing training study jointly conducted by the UCL Institute of Education and UCL Psychology and Language Departments. By using the test in this study, it was possible to determine the viability of the Chord Discrimination Test as a measure of changes in pitch perception over time. In this study, children took part in weekly singing sessions across two school terms (Spring and Summer, 2014), with the aim of assessing the impact of these activities on children’s musical development and speech and pitch perception (Welch et al., 2015). For the pitch perception assessment, one chord test from the Chord Discrimination Task was used. This was the test in the condition Chord Root C5 in Simultaneous presentation and Piano Simulation tone. Study One used this chord test in the same form as described in chapter 4, and the following research questions were examined:

1. Will HI children be capable of performing the Chord Discrimination Test?
2. How will HI children perform compared to NH children?
3. Is the Chord Discrimination Test appropriate for use in pitch assessments within musical training programmes?
4. How will children with CIs perform compared to children with HAs and children with bimodal stimulation?
5. How will children with CIs compare to adults with CIs on the Chord Discrimination Test?

In study Two, the test was expanded to include chord differences of half a semitone, to examine the following question.

1. Can NH and HI children discriminate changes in a musical chord of less than one semitone?

5.2 Study One

5.2.1 Materials and Methods

5.2.1.1 Participants

Participants were children in year one and year two at Laycock Primary School, Islington. There were 12 male and 24 female participants, ranging in age from 5 years and 5 months to 7 years and 5 months old at the first testing session. Table 5.1 dives the gender, actual age, vocabulary age and device used by the 16 HI participants, and table 5.2 gives the gender, actual age and vocabulary age of the 20 NH participants.

Table 5.1: The gender, actual age, vocabulary age and device used by 16 hearing impaired children.

ID	Gender	Actual age	Vocabulary age	Device
1	F	5 years 10 months	3 years 3 months	CI
2	M	5 years 6 months	3 years 9 months	CI
3	M	6 years 8 months	3 years 4 months	Bimodal
4	M	5 years 8 months	3 years 3 months	CI
5	F	6 years 4 months	4 years 3 months	HA
6	M	5 years 5 months	3 years 3 months	Bimodal
7	F	6 years 3 months	7 years 2 months	Bimodal
8	F	7 years 3 months	5 years 2 months	HA
9	F	6 years 9 months	3 years 3 months	CI
10	F	7 years 5 months	3 years 3 months	CI
11	M	6 years 9 months	4 years 4 months	CI
12	F	6 years 7 months	4 years 6 months	CI
13	F	6 years 10 months	3 years 7 months	CI
14	F	6 years 8 months	3 years 7 months	HA
15	M	7 years 3 months	3 years 3 months	HA
16	F	7 years 5 months	Not tested	CI

Table 5.2: The gender, actual age, and vocabulary age of 20 normal hearing children.

ID	Gender	Actual age	Vocabulary age
17	F	6 years 1 month	5 years 1 month
18	F	6 years	5 years 10 months
19	F	5 years 6 months	4 years 2 months
20	M	6 years 2 months	4 years 1 month
21	M	6 years 3 months	5 years 1 month
22	M	6 years 3 months	5 years 1 month
23	F	5 years 11 months	7 years 5 months
24	F	6 years 3 months	5 years 3 months
25	F	6 years	3 years 3 months
26	F	6 years 3 months	4 years 8 months
27	F	6 years 9 months	5 years 1 month
28	M	7 years 1 month	5 years 10 months
29	M	7 years 3 months	5 years 11 months
30	M	7 years 1 month	6 years 5 months
31	F	7 years 3 months	5 years 4 months
32	F	7 years 4 months	6 years 7 months
33	F	7 years	5 years 1 month
34	F	6 years 9 months	6 years 7 months
35	F	7 years 1 month	5 years 10 months
36	F	7 years	6 years 3 months

Children came from two different streams of the school – the mainstream classes, and the "Unit" classes, which included children with hearing impairments. A number of students had additional difficulties, and therefore the measure of vocabulary age was used as a proxy for developments stage because it was not possible to account for all of the different syndromes. The average vocabulary age for the HI children at the start of testing was 47 months (three years and eleven months) and for the NH children was 65 months (five years and five months).

5.2.1.2 Stimuli

Chord test

One chord test from Discrimination Test battery was used. This was the Simultaneous test in the Piano Simulation tone condition and Chord Root C5. This test was chosen because, in testing adults, results were generally better for Simultaneous stimuli with this chord root. As no significant difference was seen between the Sinusoid and Piano Simulation stimuli, the latter was chosen for this test as a closer approximation to musical sounds that a child might encounter. As there were no other chord combinations included in this study, the factors of Presentation Mode, Chord Root and Tone were not represented. As testing took place at three points over a six month period, a further factor of Timepoint can be added to the study. Timepoint one of testing took place in January 2014; timepoint two in May 2014; and timepoint three in July 2014. Therefore, the following factors were tested:

Factor 1: Chord Change (Middle Note, Top Note)

Factor 2: Semitone Difference (One, Two, Three)

Factor 3: Timepoint of study (One, Two, Three)

The chord test was run twice for each participant

5.2.1.3 Apparatus

The chord test was carried out largely as for previous iterations of the study, with stimuli presented on a laptop screen. Headphones were not used as several of the children were HA users or had other impairments which would make headphone use difficult or uncomfortable. Instead the children listened to the stimuli over a Behringer B205D loudspeaker set to a level of 65 dBA. Children were allowed to respond using the mouse, the laptop's touchpad, or the laptop's touch screen as they preferred.

5.2.1.4 Procedure

Testing sessions took place at Laycock Primary School in Islington, North London. Testing took place in free school room, with each child being briefly removed from their usual classroom one at a time in order to undertake the test.

5.2.2 Results

Percentage correct results were converted to a d’ score to account for the chance level. A three-way repeated measures ANOVA was carried out with the within-subject factors of Chord Change (Middle Note, Top Note), Semitone Difference (One, Two Three) and Timepoint (One, Two, Three) and the between subjects factor of Hearing Group (Normal Hearing, Hearing Impaired). Each of the main effects from this analysis will be reported under a separate heading and the interactions reported at the end.

5.2.2.1 Factor: Chord Change (Middle Note, Top Note)

There was no significant main effect of the Chord Change ($F^{(1,27)} = 0.08$, $p = 0.79$). Figure 5.1 shows the distribution of scores for this factor. As seen in the adult tests, there is a wider distribution of scores for the Top Note change, but the medians and means are similar for both changes.

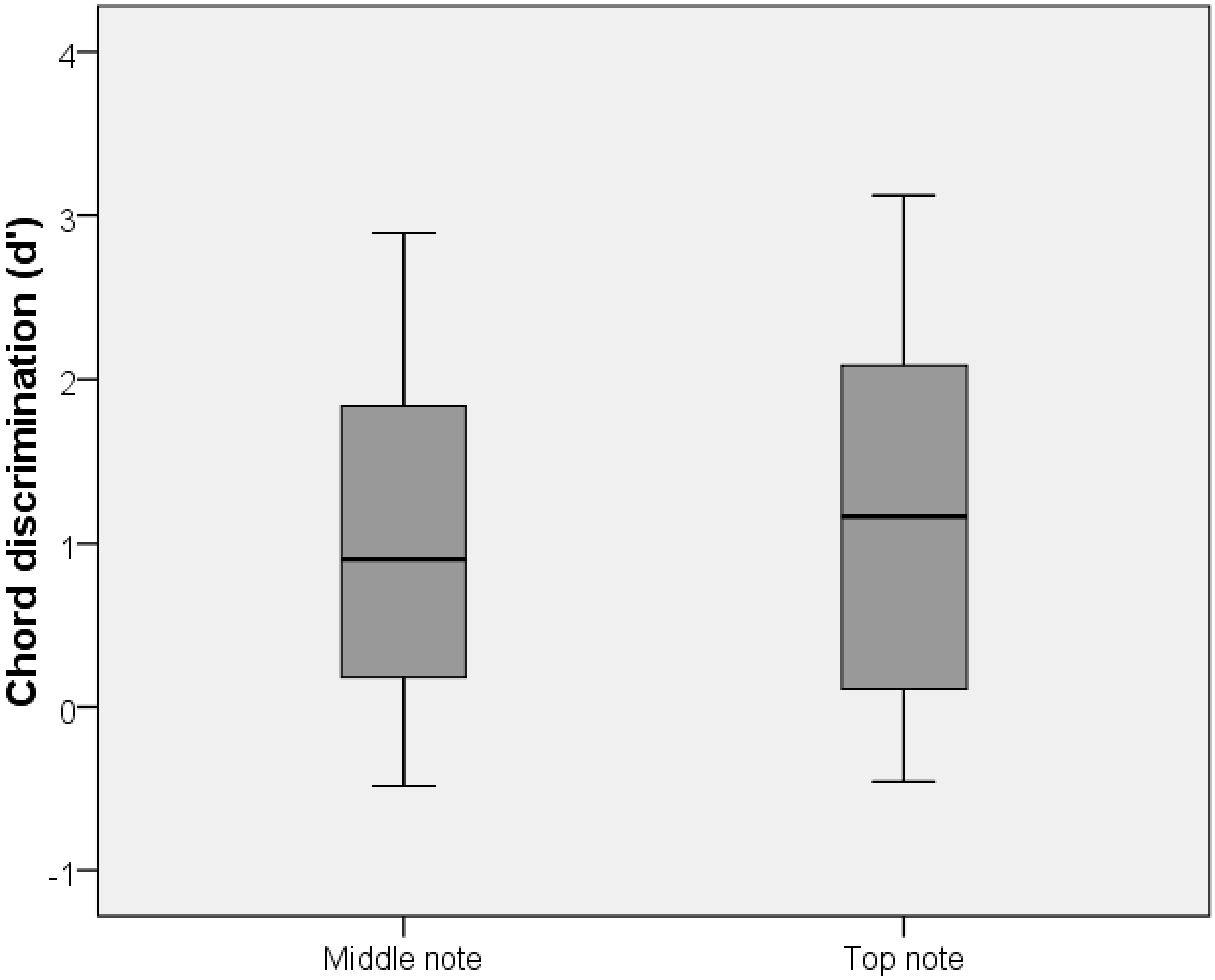


Figure 5.1: Boxplot of the distributions of scores (d') on the two Chord Change conditions. Dark horizontal lines represent the median, with the box representing the 25th to 75th percentiles, the whiskers the minimum and maximum values (apart from outliers), and an outlier represented by a circle.

5.2.2.2 Factor: Semitone Difference (One, Two, Three)

There was a significant main effect of the Semitone Difference ($F^{(2, 54)} = 23.42$, $p < 0.001$). Figure 5.2 shows the distribution of scores for this factor. Pairwise comparisons were carried out using a Least Significant Difference test, and showed that the Three Semitones condition was significantly different from the

One Semitone condition ($p = 0.001$) and the Two Semitone condition ($p < 0.001$). Participants performed above chance for all three conditions.

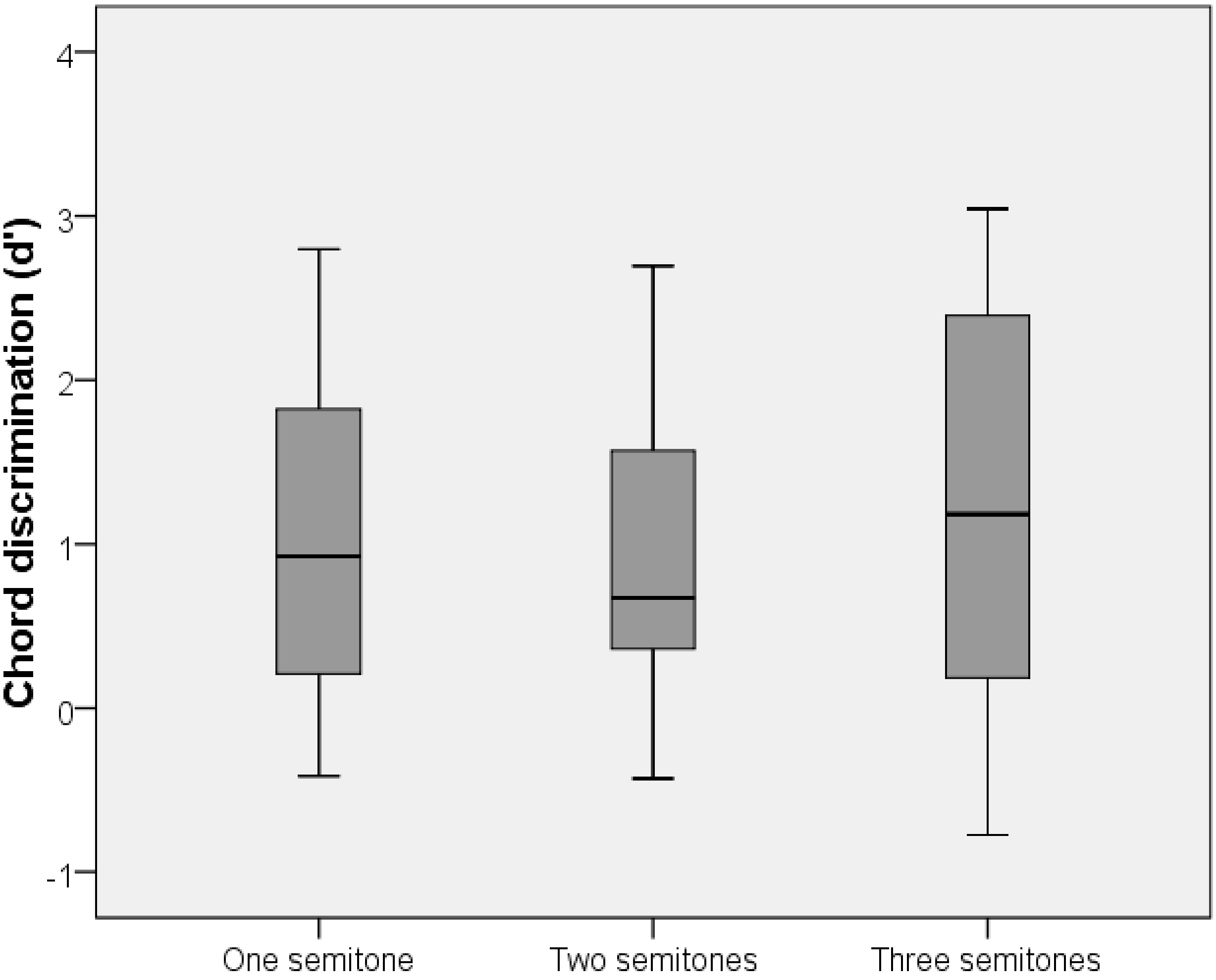


Figure 5.2: Boxplot of the distributions of scores (d') for the three Semitone Difference conditions.

5.2.2.3 Factor: Timepoint (One, two, three)

The Timepoint factor violated Mauchly's Test of Sphericity ($p = 0.037$) so results are reported using the Greenhouse-Geisser correction. There was a significant main effect of the Timepoint factor ($F^{(1.63,44.09)} = 5.03$, $p = 0.015$). Figure 5.3 shows the distribution of scores for this factor. Pairwise comparisons were carried out using a Least Significant Difference test and showed that Timepoint Three was significantly different from Timepoint One ($p = 0.007$).

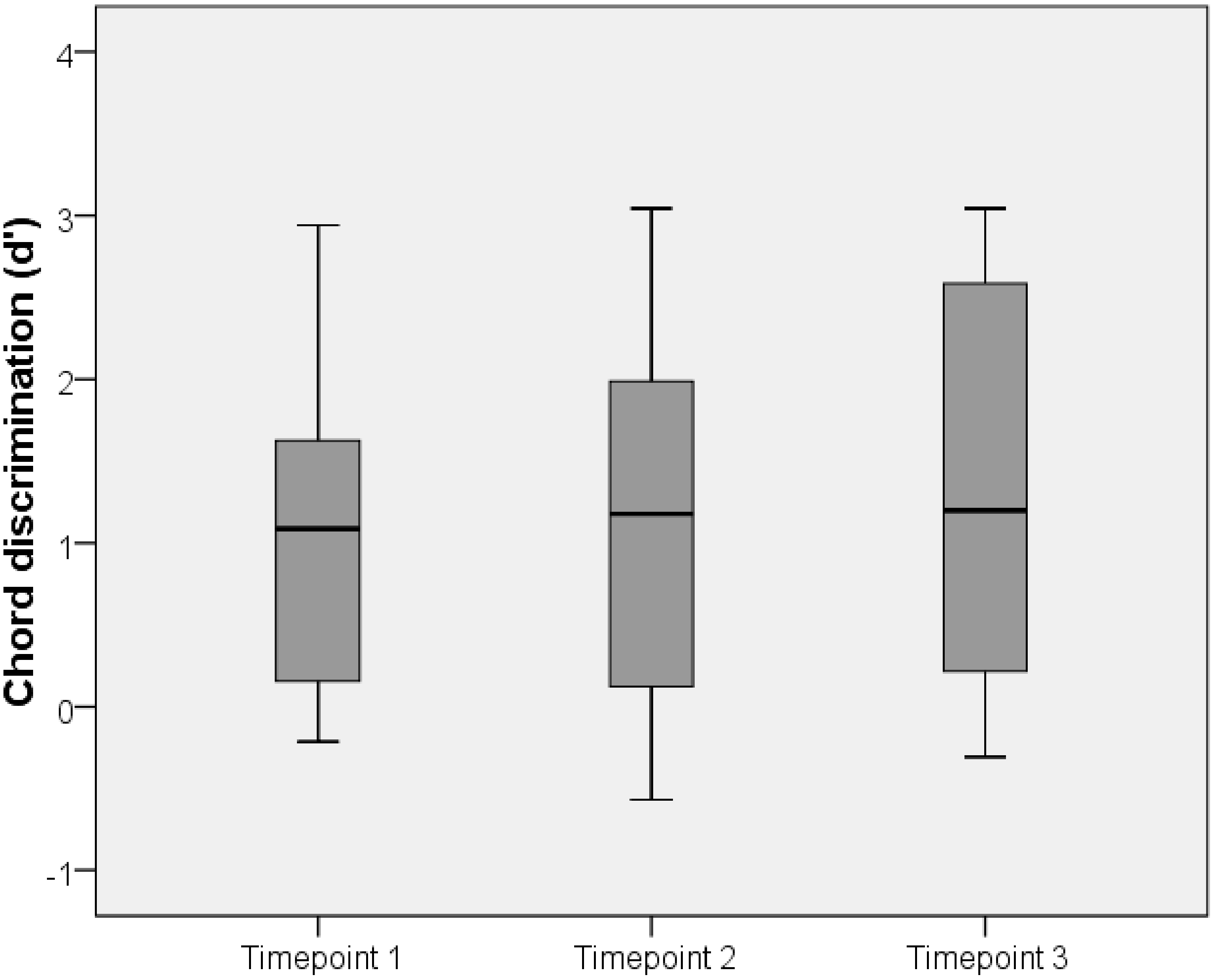


Figure 5.3: Boxplot of the distributions of scores (d') for the Timepoint conditions.

5.2.2.4: Between Subjects Factor: Group (Hearing Impaired, Normally Hearing)

Test of between subjects effects showed a significant effect of Group ($F^{(1,27)} = 20.41$, $p < 0.001$). Figure 5.4 shows the distribution of scores for the two groups.

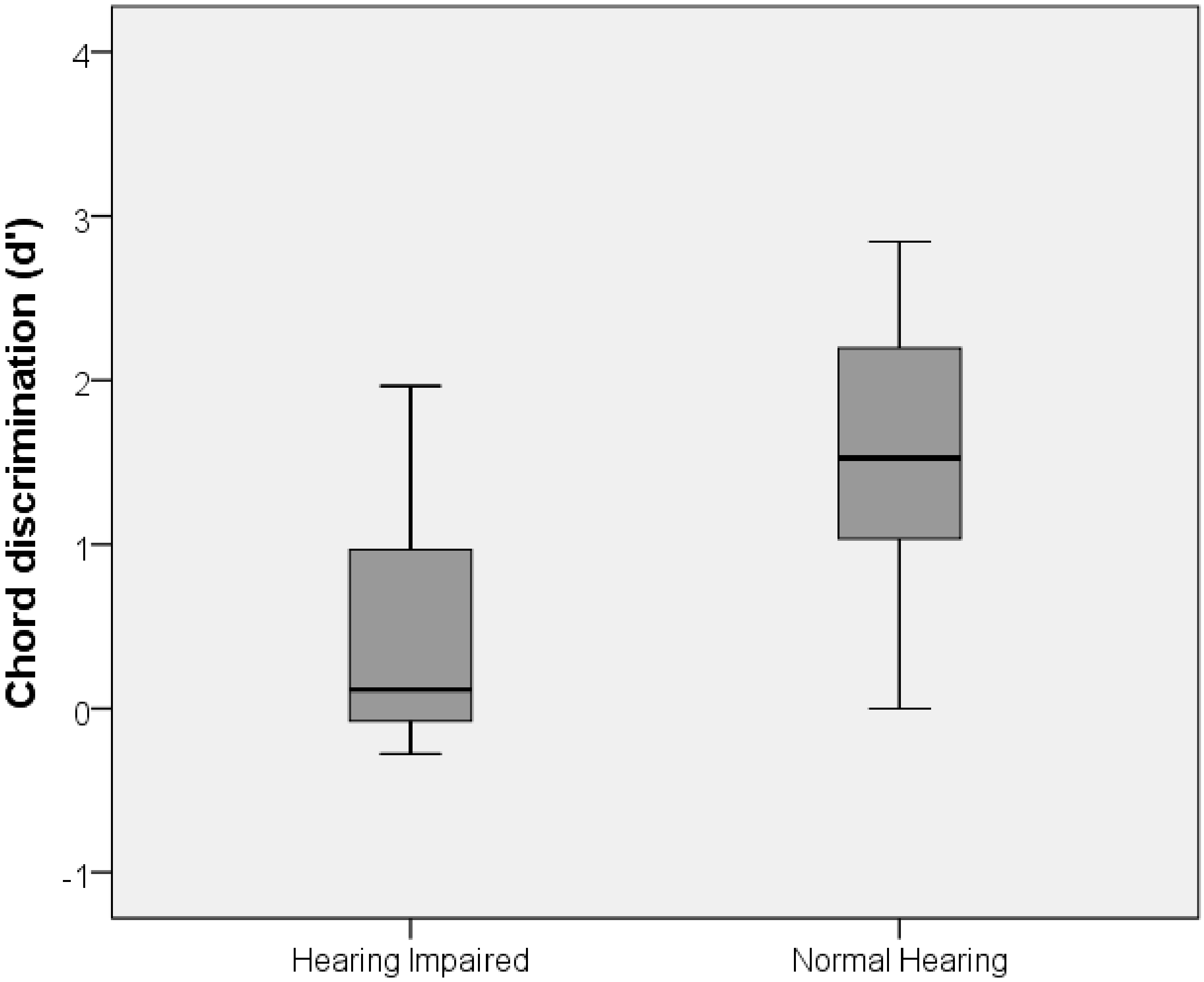


Figure 5.4: Boxplot of the distributions of scores (d') for the Group between subjects factor.

5.2.2.5 Interactions

There was a significant interaction between Semitones and Group ($F^{(2,26)} = 5.77$, $p = 0.01$). Figure 5.5 shows that the NH group performed worse when identifying the odd chord out when there was a two semitone difference between the chords, but median scores are well above chance for all three semitone conditions.

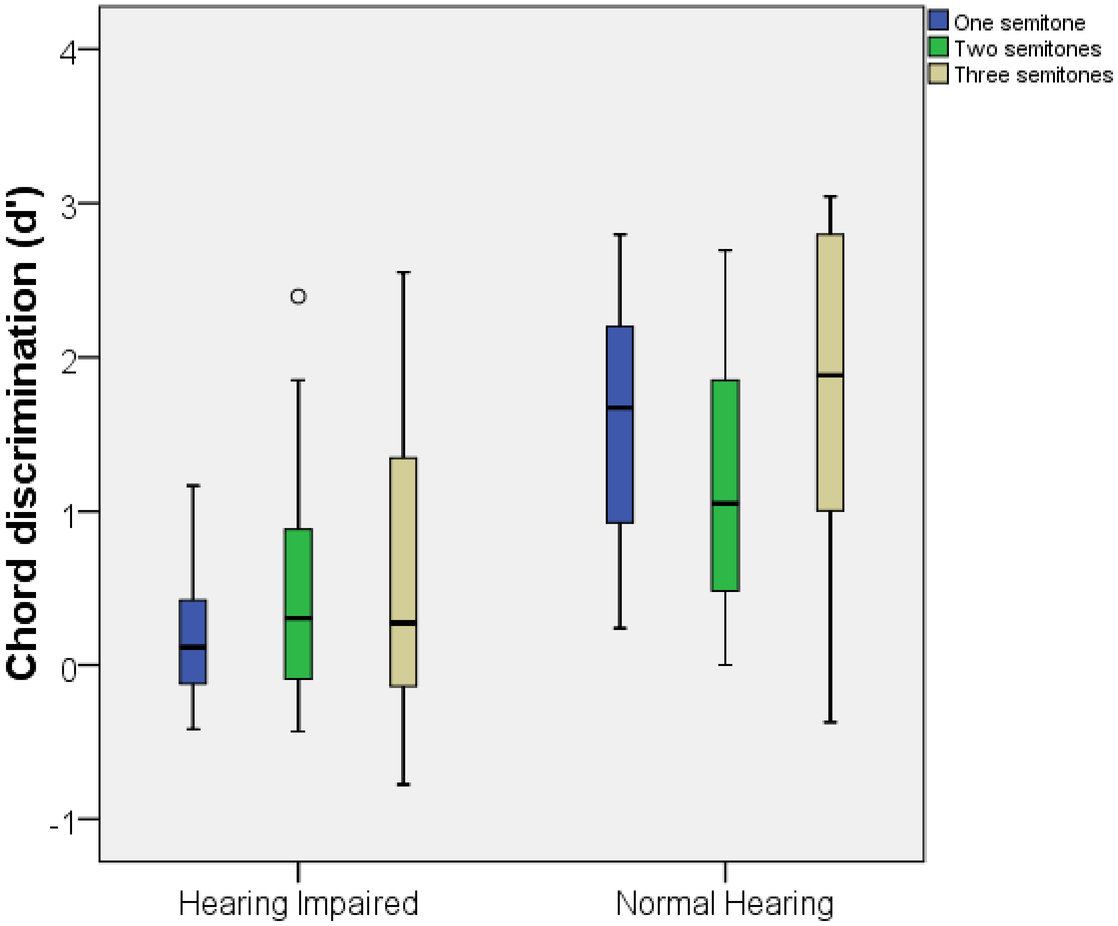


Figure 5.5. Boxplot of the distributions of scores (d') for the Hearing Impaired and Normal Hearing children, separated by semitone difference. The circle represents an outlier.

Figure 5.6 shows the distribution of scores for the NH children only for the three different Semitone Difference condition, separated by Chord Change. The worse performance on the two semitone condition remains the same for both chord changes.

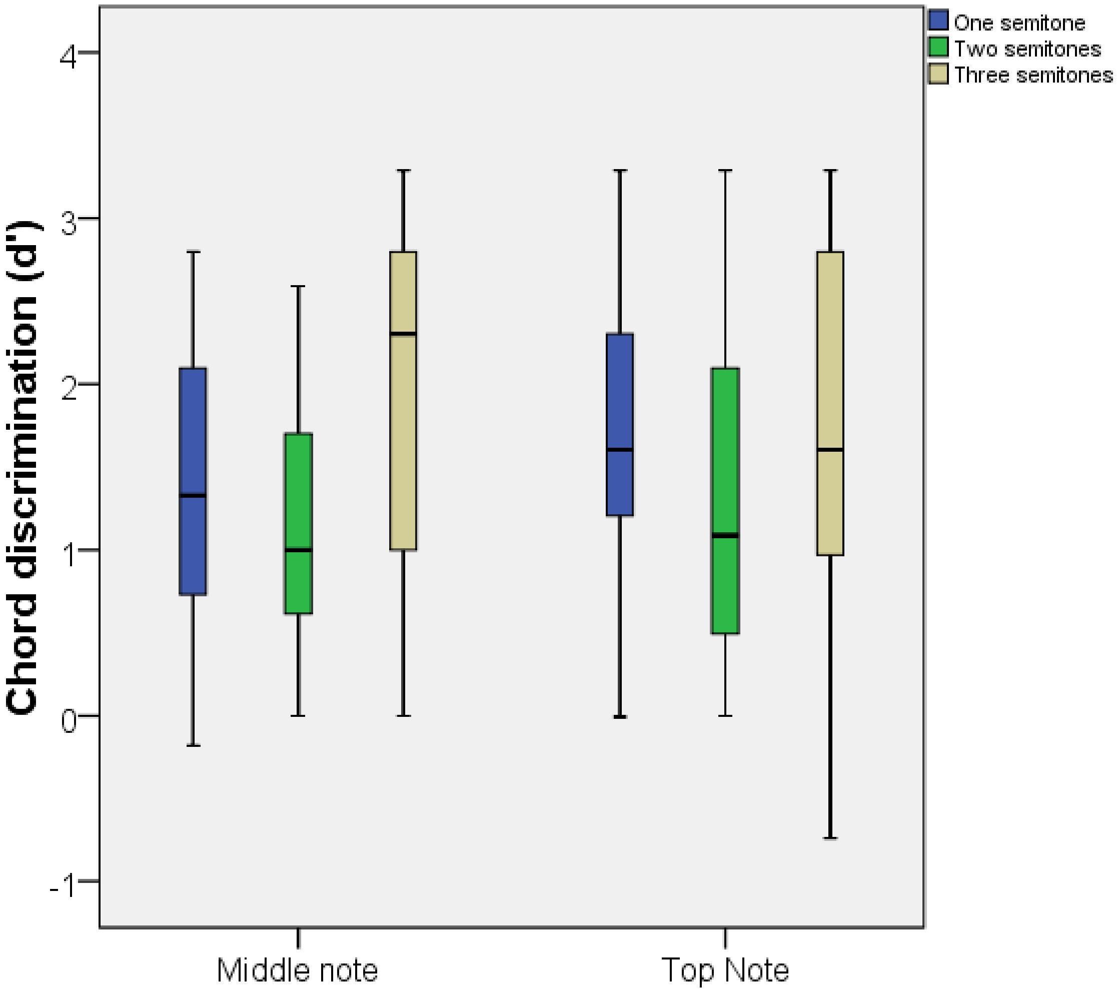


Figure 5.6. Boxplot of the distributions of scores (d') for the Normal Hearing children separated by semitone difference and chord change

5.2.2.6 Performance of hearing impaired children

A comparison of scores obtained by children with CIs, children with HAs and children using bimodal stimulation can be seen in figure 5.7. There were 9 children with CIs, 4 with HAs and 3 with bimodal stimulation. Welch's F test was conducted to account for the different number of participants in each group to compare the d prime scores of children with CIs, HAs and bimodal stimulation. This showed no significant main effect of hearing device ($F^{(2,3.906)} = 0.13$, $p = 0.88$).

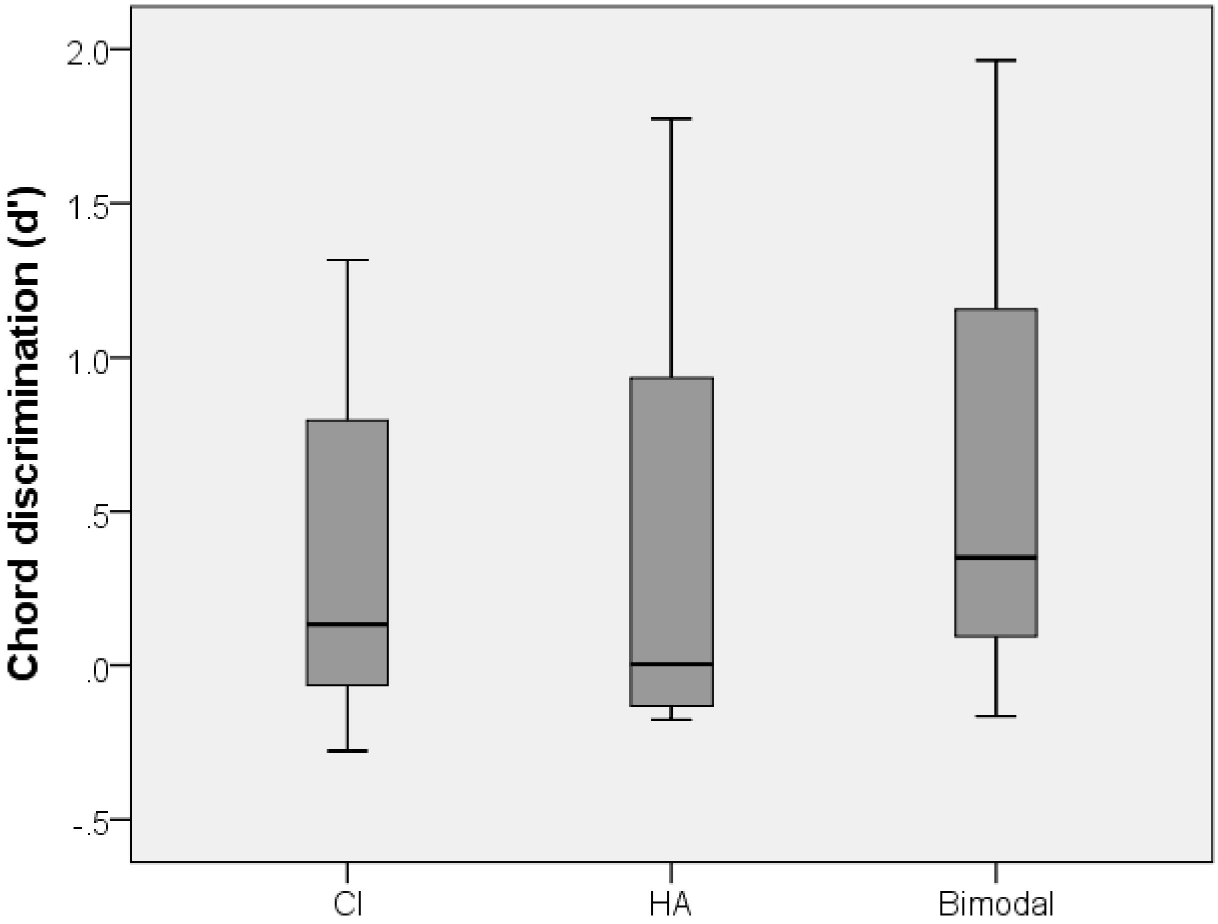


Figure 5.7: Boxplots of the distributions of scores (d’) for children with CIs children with HAs and children using bimodal stimulation for the three semitone conditions.

5.2.2.7 Comparison with adults

A Mann-Whitney U test was run between the scores of the children with CIs on this test at Timepoint Three and the average scores of the adults with CIs who took part in the study described in chapter 4 on the same section of the Chord Discrimination Test. Non-parametric testing was used due to the disparity in number of participants between the two groups (18 adults, 9 children). There was a significant difference between the scores of the adults and the children (U = 26, p = 0.005). Figure 5.8 shows the distribution of scores for the adults and children on this task. It shows that the median score for the adults was well above chance, whereas the children were only slightly above chance. There were two extreme outliers achieving exceptionally high scores amongst the children with CIs. These two children had vocabulary ages of 3 years 4 months (d’ score of 1.78) and 5 years 4 months (d’ score of 2.8) (actual ages 6 years 2 months and 7 years 1 month).

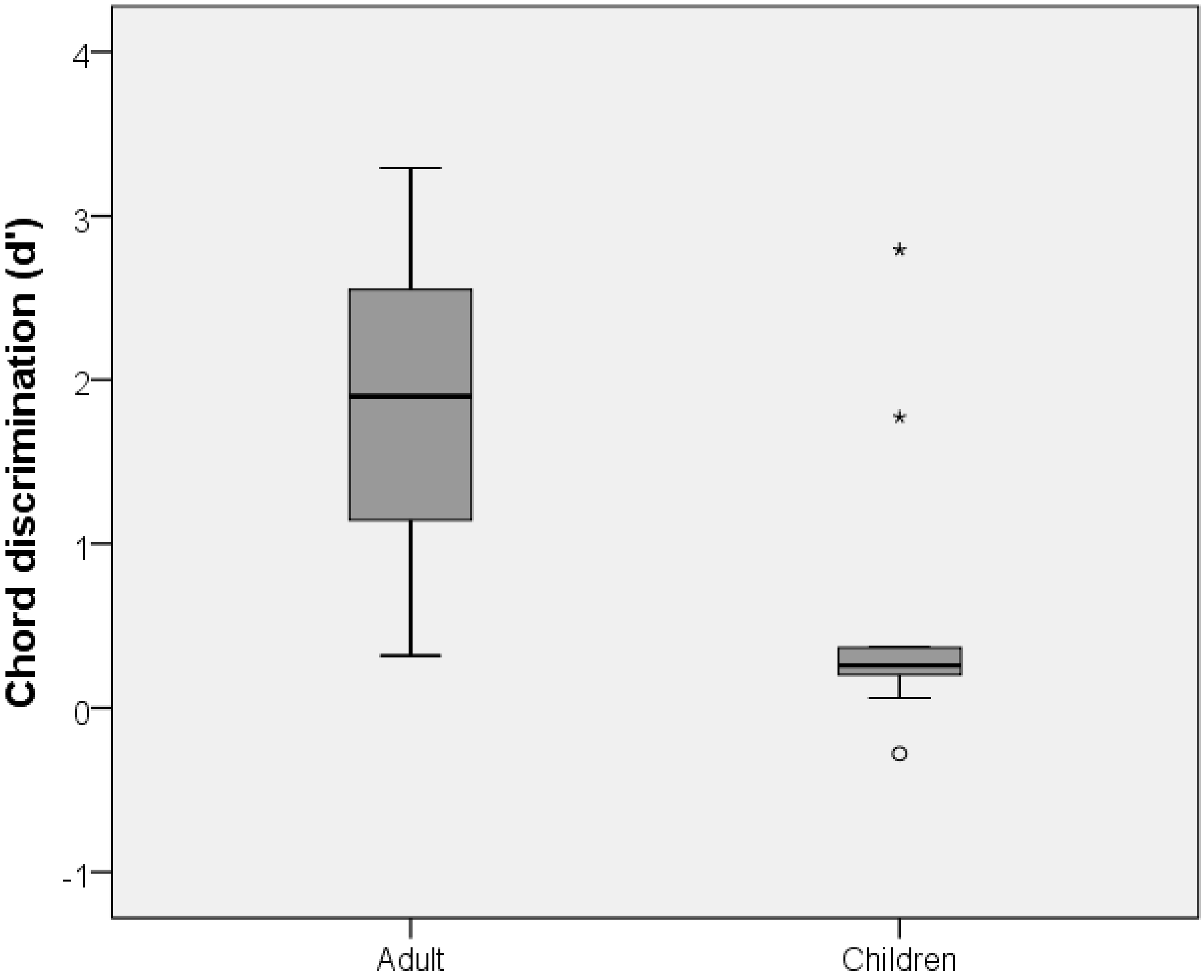


Figure 5.8: Boxplots of the distribution of scores for Adults with CIs and Children with CIs on the sections of the Chord Discrimination Test used in this study (Chord Root C5, simultaneous presentation, simulated piano tones).

5.2.3 Discussion for Study One

In this study, a part of the Chord Discrimination Test was carried out with NH and HI children. One aim of doing this was to find out whether children, particularly those with HI, will be capable of performing this test. The findings of this study showed that children taking part in the study which involved identifying one, two and three semitone differences in musical chords were on average above chance at identifying the changed chord, particularly in the three semitone condition. This indicates that the test is appropriate for use with children. There were a few children tested who did not appear to fully understand what was asked of them. The interface of the test shows three boxes, numbered one, two and three, each of which lights up in turn as the chord plays. Some children would automatically answer each successive question with whichever box (2 or 3) had been correct in the previous question. This may have been a result of the fact that many children tested had a lower vocabulary age than their actual age, particularly those with HI. There is evidence to suggest that vocabulary age can be used as an indicator of developmental stage (Bloom, 1993; Hoff, 2005). However, the fact that overall children scored above chance would suggest that most children were able to comprehend what was being asked of them and answer appropriately.

HI children scored significantly worse than NH children on this task. Comparing average scores across all the tests, HI children were scoring on average just above chance levels, while the NH children were well above chance. This is in keeping with previous findings that HI children are outperformed by NH children on pitch perception tasks (Looi & Radford, 2011; Edwards, 2013). An interesting finding with regards to the difference between the performance of HI and NH children is the pattern for NH children’s performance to drop when identifying a chord change of two semitones, as compared to one or three. This is possibly due to the fact that, for the two semitone change, all the notes of the chord remain within the C Major scale. By contrast, when the chord changes by one semitone or three semitones, the new notes in the chord are not part of the C major scale, making the change more apparent as they may sound more dissonant to the listener. This is in keeping with previous work by Krumhansl (1990), which has suggested that intervals which are readily available in the diatonic scale are perceived as more consonant.

Previous studies have found that children with CIs are outperformed both by children with HAs and children with bimodal stimulation (Looi & Radford, 2011; Edwards, 2013). In the present study, within the HI group, there was no significant different found on performance on the Chord Discrimination Test based on hearing device used, which goes against these earlier findings. However, this may be due to the fact that there was a disparity in numbers between the three groups, with nine children using CIs compared to four with HAs and three with bimodal stimulation.

An improvement was seen in tests scores on the third timepoint (carried out in July 2014) compared to the first timepoint (January 2014). This suggests that the Chord Discrimination Test is appropriate for use in pitch perception assessments in musical training programmes, as the test was able to pick up differences over time. The better results at timepoint three may be due to increased familiarity with the tests and understanding of what was being asked for, as well as the impact of the weekly singing lessons they were undertaking during this time. HI children generally report a greater enjoyment of music, and higher appraisal of songs, than adults with CIs (Nakata et al., 2005; Hopyan et al., 2011). The children's enjoyment and enthusiasm in taking part in both the singing lessons and the musical chord test is likely to have contributed to their improved performance over time. Additionally, training programmes of a musical nature have been shown to have a beneficial effect on pitch perception abilities of HI children (Chen et al., 2010; Nardo et al., 2015).

A comparison was made between the scores attained by adults who took part in the study described in chapter 4 and that of children with CIs taking part in this study, looking at the same element of the Chord Discrimination Test (Chord Root C5, simultaneous presentation, piano simulation tone). There was a significant difference between the two groups, with median score for the adults well above chance, whereas the children were only slightly above chance. This goes against previous findings that children with CIs outperform adults with CIs on pitch tests (Looi, 2014). This could be a result of the fact that many of the children tested here had a lower vocabulary age than their actual age, suggesting a developmental delay. The HI group had an average vocabulary age of three years and eleven months, but taking the CI users separately, the average vocabulary age dropped to three years and eight months. This very low vocabulary age, and the early developmental stage it suggests, makes it difficult to directly compare this group to adult CI users.

5.2.3.1 Rationale for Study Two

Although performance was significantly better when participants were identifying the changes in the chord with a three semitone difference compared to one semitone, the group of children as a whole were above chance at recognising the changed chord when the difference was only one semitone. In addition, all NH children were above chance at identifying the changed chord at the one semitone difference. Because of this, it was hypothesised that some children might be able to recognise the changed chord when the difference was only half a semitone.

5.3 Study Two: Half Semitone Discrimination

Following Timepoint Three, a number of children undertook a modified version of the chord test which included an extra condition in the Semitone Difference factor which tested their ability to recognise the changed chord when the difference was half a semitone. This testing took place in January 2015.

5.3.1 Materials and Methods

Participants were children who had been in Year One during Study One, and were now in Year Two. Table 5.3 gives the age, hearing status and management of hearing impairment (where applicable) for the sixteen participants.

Table 5.3: Age at testing, hearing status and management of hearing impairment (where applicable) for the sixteen children who undertook the modified Chord Discrimination Test. Key to abbreviations: HI = hearing impaired, NH = normally hearing, CI = cochlear implant, and HA = hearing aid. Bimodal indicates that the child wore a cochlear implant in one ear and a hearing aid in the other.

ID	Age at test	Hearing status	Management for HI (if applicable)
1	6 years 10 months	HI	CI
2	6 years 6 months	HI	CI
3	7 years 8 months	HI	Bimodal
4	6 years 8 months	HI	CI
5	7 years 4 months	HI	HA
6	6 years 5 months	HI	Bimodal
7	7 years 3 months	HI	Bimodal
8	6 years 11 months	HI	HA
9	7 years 1 month	NH	NA
10	7 years	NH	NA
11	6 years 6 months	NH	NA
12	7 years 2 months	NH	NA
13	7 years 3 months	NH	NA
14	7 years 3 months	NH	NA
15	7 years 3 months	NH	NA
16	7 years 2 months	NH	NA

Stimuli for this test differed only in the inclusion of a half semitone condition in the Semitone Difference factor. Procedure was identical to that in Study One.

5.3.2 Results

Percentage correct results were converted to a d' score to account for guesswork. A repeated measures ANOVA was carried out to detect significant main effects of the two within subjects factors (Chord Change, and Semitone Difference) and the between subjects factor (Group).

5.3.2.1 Factor: Chord Change (Middle Note, Top Note)

There was no significant main effect of the Chord Change ($F^{(1,14)} = 1.36$, $p = 0.23$). Figure 5.9 shows the distribution of scores for this factor.

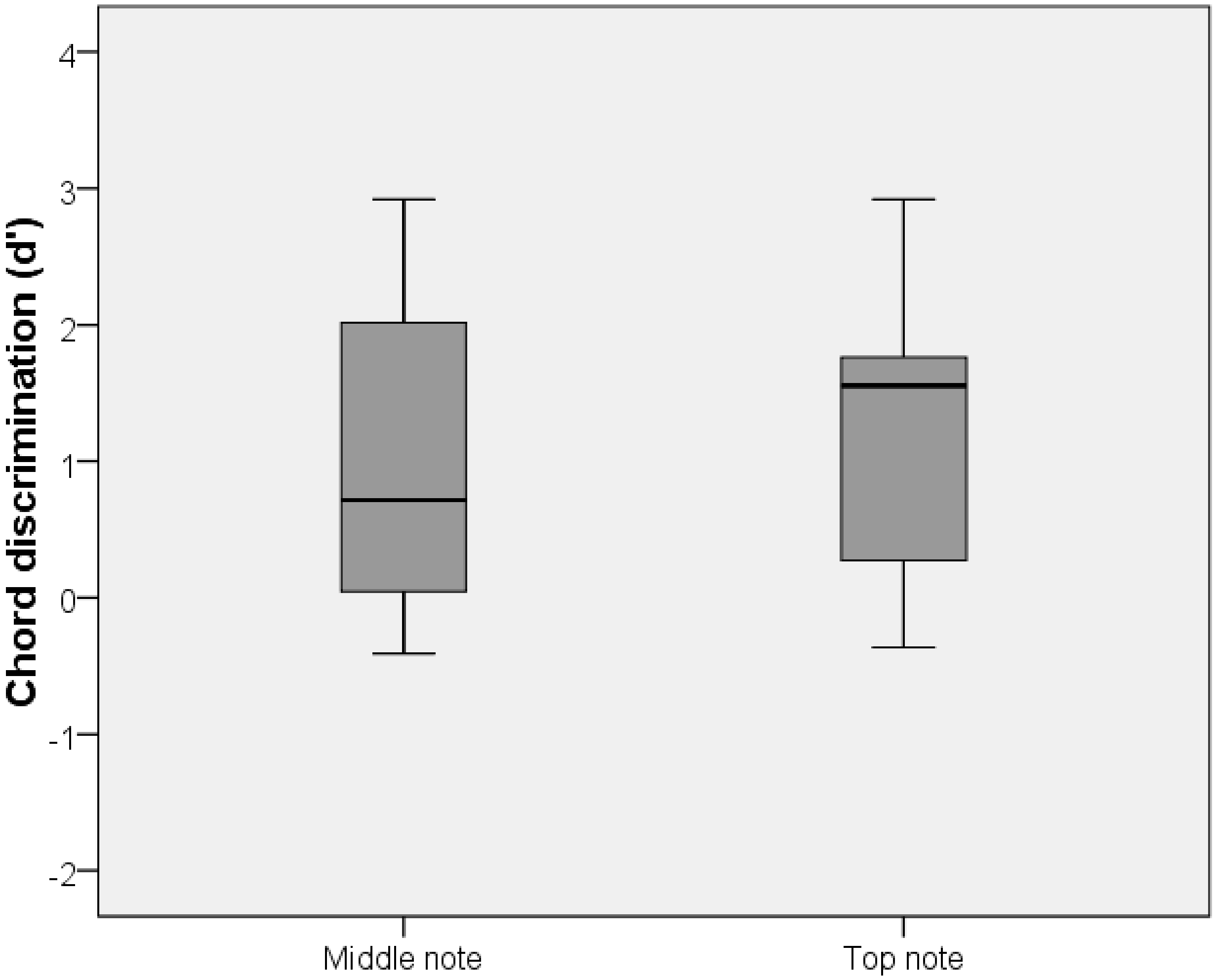


Figure 5.9: Boxplot of the distributions of scores (d') for the Chord Change factor in the modified chord test.

5.3.2.2 Factor: Semitone Difference (Half, One, Two, Three)

There was a significant main effect of the Semitone Difference factor ($F^{(3,42)}$ = 3.66, p = 0.02). Figure 5.10 shows the distribution of scores for this factor. Pairwise comparisons were carried out using a Least Significant Difference test, and showed that the Half Semitone condition was significantly different from the One Semitone condition (p = 0.017), the Two Semitones condition (p = 0.02) and the Three Semitones condition (p = 0.035).

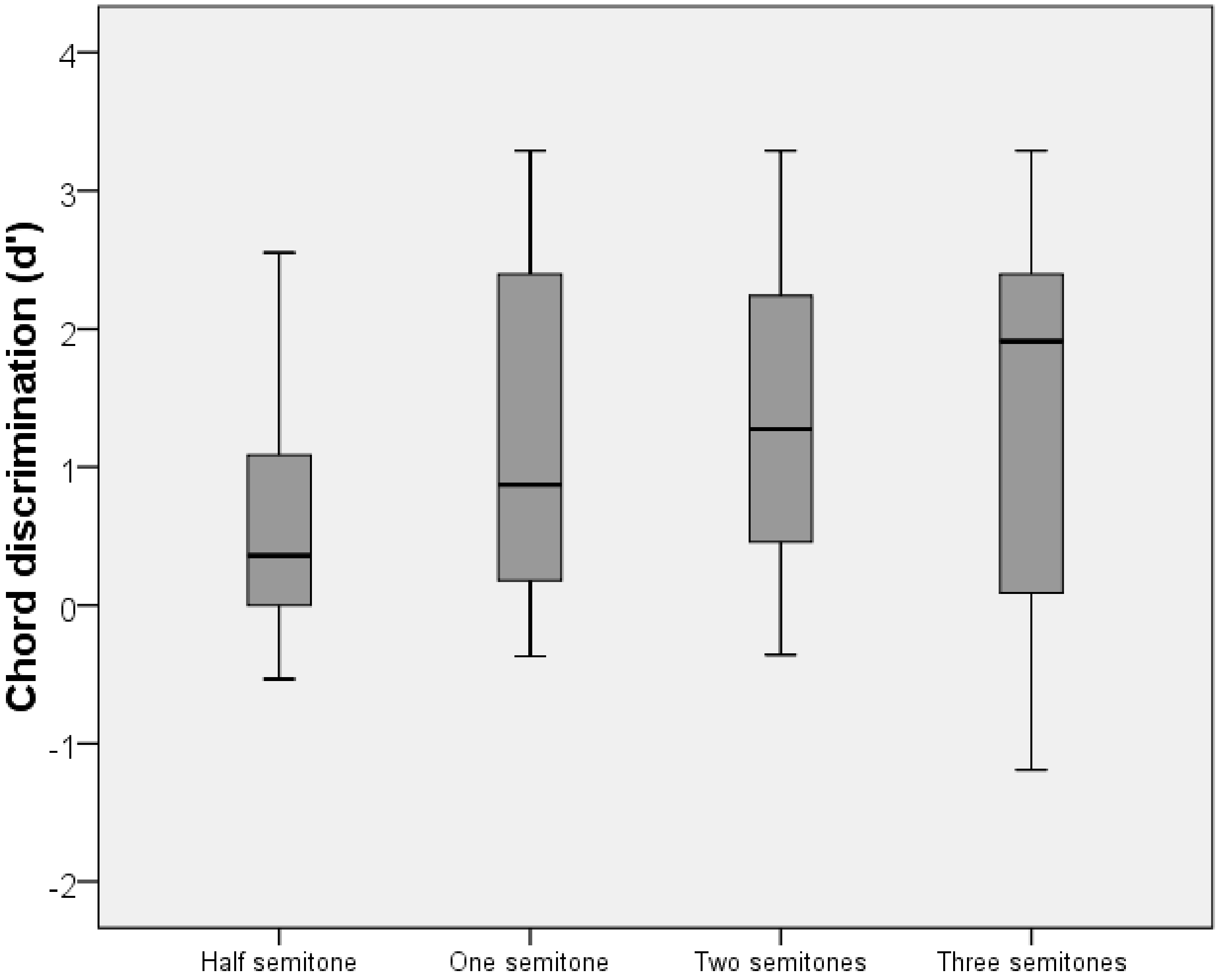


Figure 5.10: Boxplot of the distributions of scores (d') for the Semitone Difference factor in the modified chord test.

5.3.2.3 Between Subjects Factor: Group (Hearing Impaired, Normally Hearing)

Test of between subjects effects showed a significant effect of Group (p = 0.001). Figure 5.11 shows the distribution of scores for the two groups.

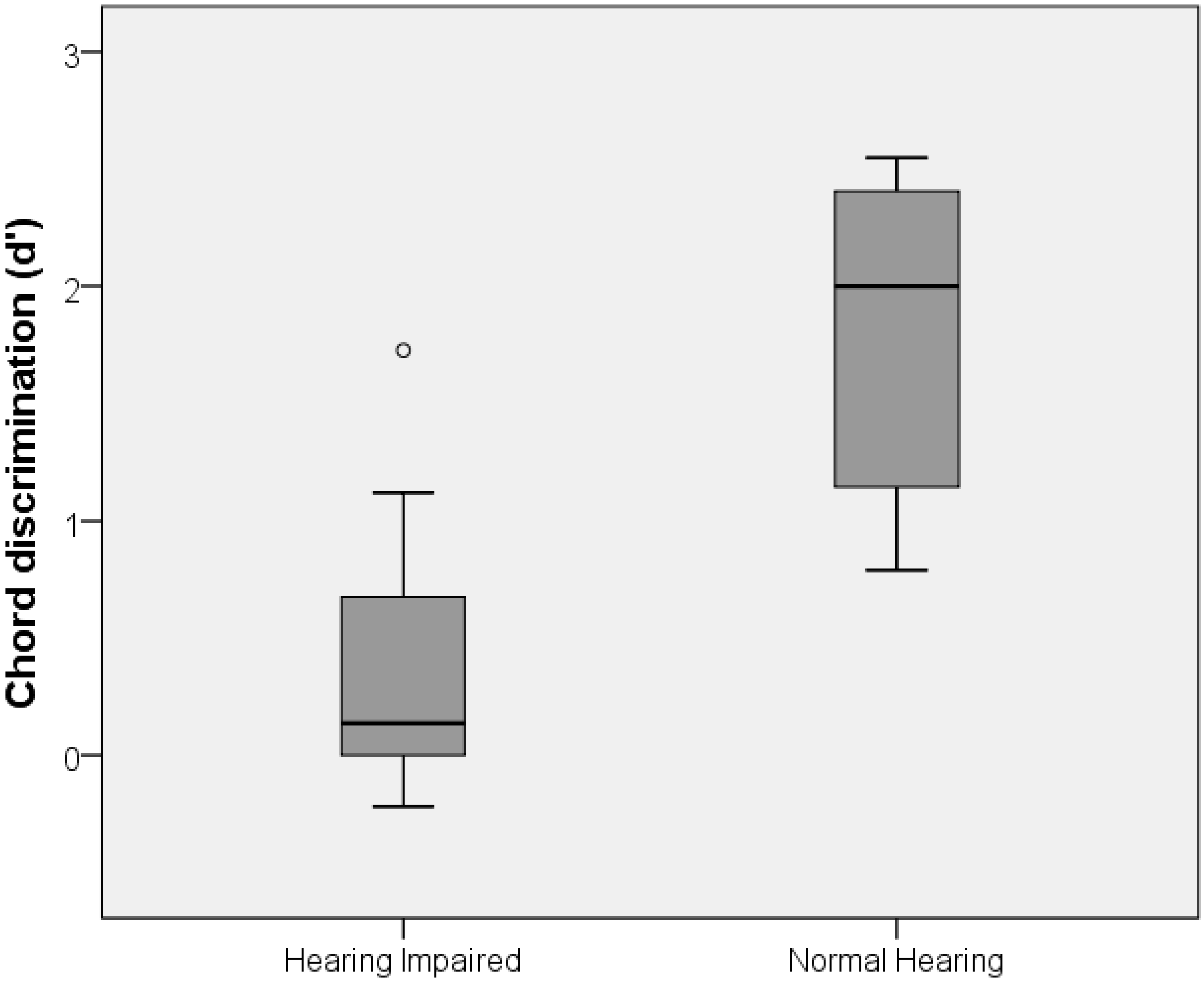


Figure 5.11: Boxplot of the distributions of scores (d') for Group between subjects factor in the modified chord test.

5.3.2.4 Identifying the half semitone change

HI children scored on average at chance when identifying a half semitone change in a Middle Note context, but above chance in a Top Note context. Normally hearing children scored well above chance in both chord changes. Figure 5.12 shows the distribution of scores (d') for the hearing impaired and normally hearing children on the half semitone discrimination task. Figure 5.13 shows the distributions of scores for all four semitone conditions for the NH and HI children. The NH groups show the same drop in mean scores from the 1 semitone condition to 2 semitones as seen in Study 1. HI children perform at chance in the half semitone condition. The interaction between Semitones and Group was not significant ($F^{(3,12)} = 1.15$, $p = 0.34$).

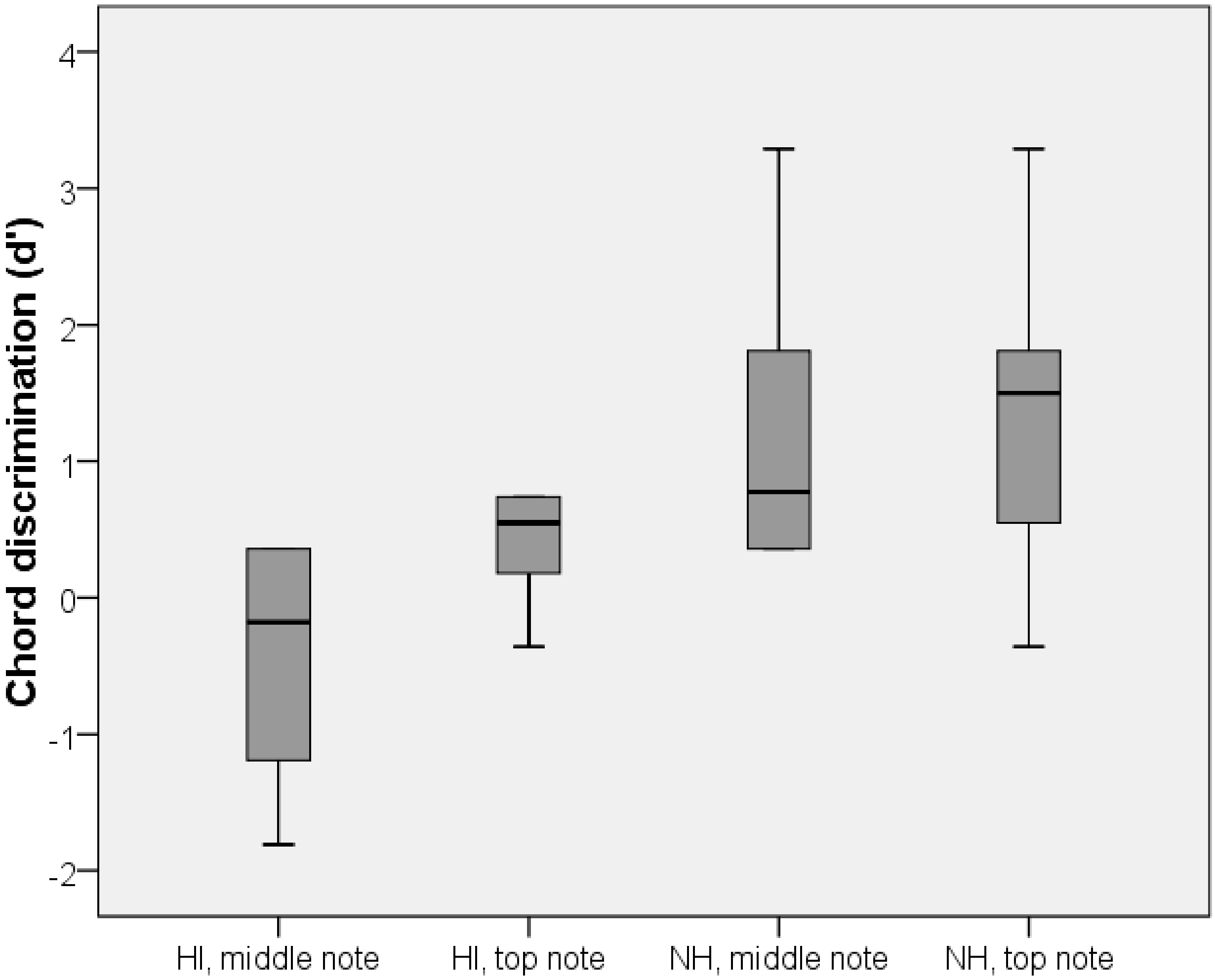


Figure 5.12: Boxplot of the distributions of scores (d') for the normally hearing and hearing impaired children for the Half Semitone condition of the Semitone Difference factor in the modified chord test.

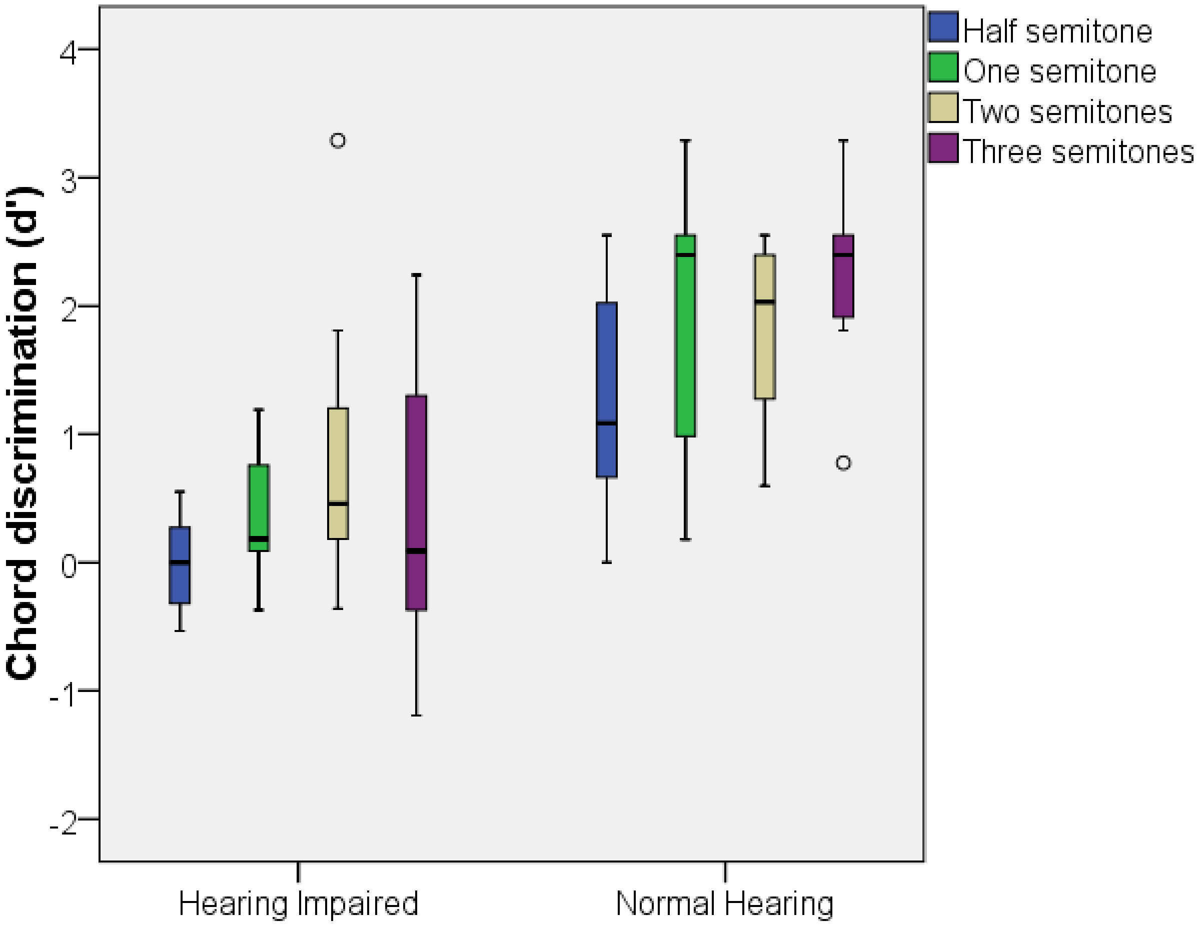


Figure 5.13: As for figure 5.1. Boxplot of the distributions of scores (d') for the normally hearing and hearing impaired children, separated by number of semitones. Circles represent outliers.

A breakdown of the HI children's performance on the half semitone test can be seen in table 5.4. Each child's vocabulary age is given where available as well as their d prime score on the half semitone test for the Middle Note and Top Note conditions. Scores above chance are highlighted in grey.

Table 5.4: The d prime score on the half semitone test for the HI children for the Middle Note and Top Note conditions along with their vocabulary age where available.

ID	Middle note	Top Note	Vocabulary age
1	-1.19	0.74	3 years 3 months
2	0	0	3 years 9 months
3	0.36	0.36	3 years 4 months
4	-0.36	0.74	3 years 3 months
5	0.36	0.74	4 years 3 months
6	-1.19	0.36	3 years 3 months
7	-1.81	0.74	7 years 2 months
8	0.36	-0.36	Not tested

Figure 5.14 shows the distribution of scores for the normally hearing children for all of the semitone conditions separated by chord change. Only the Top Note chord change condition shows the pattern of falling scores for the two semitone difference.

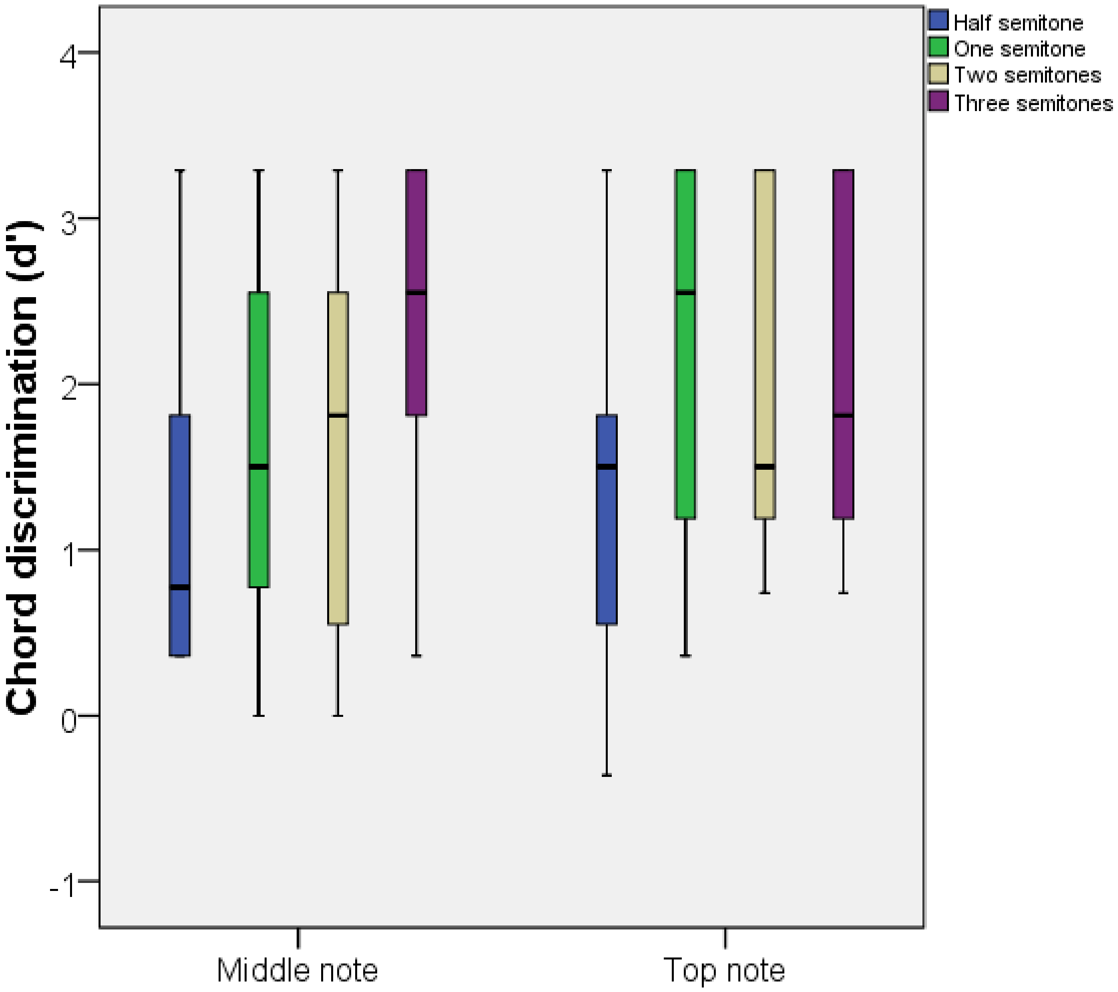


Figure 5.14. Boxplot of the distributions of scores (d') for the Normal Hearing children separated by semitone difference and chord change.

5.3.3 Discussion for Study 2: Half Semitone test

Overall the children tested here were significantly worse at detecting the half semitone difference than any of the other semitone conditions, though still averaging above chance overall. As this half semitone difference is not usually heard in musical chords, its unfamiliarity could be a factor in it being a more challenging test for the HI children. This finding is in keeping with earlier studies showing HI children have difficulty in discrimination small pitch changes

(Vongpaisal et al., 2006). Despite this, six out of the eight HI children were above change in the Half Semitone condition when the changing note was the top note of the chord. Despite the difficulty of the half-semitone task, the NH children still averaged well above chance when the half semitone change occurred in the Top Note of the chord. This concurs with the results of the main study where participants showed a better performance in the Top Note condition. As with that study, it is likely here that the change occurring at the highest note of the chord made it easier to discern, in keeping with findings by Huron (1994) that changes in the outer notes of an auditory stream are more apparent that inner changes.

5.4 Overall conclusions and future directions

The results of this study are in concord with previous research showing that HI children are outperformed by NH children on pitch-related tasks. The fact that NH and HI children were (with a few exceptions) able to understand and perform the task, and that results improved over the course of the singing training programme, demonstrate that the Chord Discrimination Test is suitable for use in assessing the impact that music training programmes have on pitch perception in children. As the study described here used only one test from the battery, future testing using the whole battery with NH and HI children would be useful for a number of reasons. Firstly, it would provide clues to any necessary amendments that might make the test easier to follow for the few children who found it difficult to comprehend; and secondly, it would give a fuller picture of the abilities of children to perceive small changes in musical chords in both in simultaneous (harmonic) and sequential (melodic) contexts.

The Chord Discrimination Test also has a potential for use in a number of different arenas with regards to children's pitch perception. It has been shown to be appropriate for use in musical training programmes. There is evidence to suggest that musical training benefits the neural encoding of speech (Patel, 2011). Children's pitch perception abilities have been shown to be related to phonological processing and reading abilities (Anvari et al., 2002; Forgeard et al., 2008), and musical training can enhance reading and the perception of pitch in speech (Moreno et al., 2009). Music listening and training in children can enhance developmental skills such as attention (Strait and Kraus, 2011), identifying and understanding emotion (Hopyan et al., 2011), cognitive skills (Conway et al., 2009) and early language skills (Carr et al., 2014). The Chord Discrimination Test could also be used in clinical audiological practice, for example as an element of assessment of music perception in children. The test is adaptable and can be used to examine various aspects of music perception such as pitch, harmony, melody and timbre, which are aspects of music that are difficult for HI listeners, particularly those with CIs (Gfeller et al., 2002; 2002b). There is therefore great scope for the use of the Chord Discrimination Test in children, either as an assessment of pitch in training programmes, or as an element of the music-related training itself, with the aim of improving speech and reading abilities in children.

An additional application of the Chord Discrimination Test arises out of the finding that performance of NH children was worse when the changing note remained within the C major scale of the standard chord. This suggests there is a sensitivity to musical scales available to NH children, but not HI children, and that the Chord Discrimination Test is able to uncover this sensitivity. This brings scope for the test to be used in a variety of contexts, such as in musical instruction for children involving scales. Previous research has shown that children with some musical training in Western music are better at identifying mistunings in familiar Western scales than in non-Western scales, and also outperform children without musical training on this task (Lynch & Eilers, 1991). The design of the Chord Discrimination Test allows it to be adaptable for examining the perception of such mistunings in scales.

The sensitivity of the Chord Discrimination Test to examining perception of musical scales could also make it appropriate for use with patients with amusia, the inability to recognise or reproduce musical tones (Peretz et al., 2002). Studies have shown that infants show a preference for musical scales with unequal steps (Trehub, 1999), however, individuals with amusia are typically unable to detect the pitch changes that make up a scale (Peretz et al., 2002). This aspect of the Chord Discrimination Test could therefore allow it to be useful in assessments or research with these patients.

5.5 Summary of findings

1. HI children were on the whole capable of performing the Chord Discrimination Test

2. HI children were outperformed by the NH children on the test

3. Performance on the task improved with repeated session, showing that the Chord Discrimination Test is sensitive enough to identify changes in performance over time. The improvement may be due to familiarity with the task or to attendance at a training programme involving regular singing lessons.

4. There was no significant different between scores for children with CI, children with HAs and children with bimodal stimulation, but participant numbers for the latter two groups were low.

5. Performance on the Chord Discrimination Test was significantly worse for children with CIs than for adults with CIs.

6. NH children were above chance at recognising a half-semitone change in a musical chord, and 75% of the HI children could recognise the half semitone change when it occurred in the top note of the chord. However, this task is significantly more difficult than identifying one, two or three semitones.

7. Results suggest that the Chord Discrimination Test can be applicable for use with children in several contexts, such as in musical training programmes, clinical assessments of music perception, or in research or assessments involving aspects of musical scales.

Chapter 6 - Discussion and conclusions

6.1 General discussion

The research detailed in this thesis examined the subjective experience of music that current day CI users have; pitch perception for CI users in the context of musical chords; and the relationships between these two aspects of a CI users' musical experience. Examining pitch in a musical context was chosen due to the fine discrimination in pitch needed in order to recognise meaningful differences in a musical piece. For CI users, this fine pitch discrimination is difficult to achieve due to the way CI processing strategies deliver sound. Musical chords were used in the test battery as they are a very common component of Western music which have been rarely examined in the context of CI-assisted hearing. Furthermore, musical chords retain essential qualities regardless of whether the notes are played simultaneously or sequentially. This study was unique in making an assessment of CI users' perception of pitch in musical chords in both simultaneous and sequential presentation, and in examining the parameters of musical chords which might provide useful information about CI users' pitch perception in musical contexts. Through evaluating a number of different parameters, a test battery was optimised which examined the effects on CI users' pitch perception of variations in the presentation, chord root, chord change, and semitone difference between chords.

The research described in this thesis was carried out to address gaps in the literature regarding music for CI users. Firstly, while there has been a great deal of work examining the perception of various aspects of music such as pitch, melody and rhythm in CI users, there was a scarcity of literature addressing the perception of musical chords (McDermott, 2004). Secondly, this research was the first to compare the experiences of pre-lingually deafened and post-lingually deafened adult CI users, in both subjective and objective measures.

6.1.1 Subjective experience of music for CI users

Questionnaire studies have often shown a generally negative experience of music for CI users, finding that up to a third of CI users do not enjoy listening to music with their implants (Leal et al., 2003; Gfeller et al., 2000), appreciation of music is generally vastly reduced compared to the period prior to their hearing loss (Mirza et al., 2003) and many CI users choose not to listen to music at all (Mirza et al, 2003; Lassaletta et al., 2008). Chapter 2 described a questionnaire validation and a study which was carried out to examine current attitudes amongst CI users towards their experience on listening to and enjoying music. The questionnaire chosen here to bring the research evidence up to date was that used by Mirza et al. (2003). This questionnaire, intended for post-lingually deafened adults who had been given a CI, included a wide variety of questions covering listening to, enjoying, and performing music. As this questionnaire was over a decade old, the aim for repeating it was to bring evidence up to date regarding CI users' attitude towards music in the current decade, and to devise a more comprehensive questionnaire, with questions relevant to many possible phases and experiences of hearing loss, both pre- and post-lingual.

The CI users who responded to the questionnaire spent more time listening to music, and reported greater enjoyment, than those responding to earlier studies (Mirza et al., 2003; Leal et al., 2003; Gfeller et al., 2000; Lassaletta et al., 2008). This may be due to improvements in CI technology, or to a bias amongst this particular group of participants to be particularly interested in their music listening experience. However, music was still a disappointing experience for many respondents, in particular for those who previously participated in musical activities such as singing or playing a musical instrument.

A significant finding of the questionnaire study described in chapter 2 was that pre-lingually deafened respondents were much more likely to report enjoying listening to music much or very much than were post-lingually deafened participants. This is probably due to the pre-lingually deafened not comparing their CI music listening experience negatively to a memory of listening to music with normal hearing. This is supported by the fact that children with CIs, who also have no memory of music with normal hearing, are much more likely to report enjoyment of music than adults with CIs (Nakata et al., 2005; Hopyan et al., 2011).

A finding from the free text sections of the questionnaire was that melody and harmony were difficult to distinguish, with an overall effect described as overwhelming. This is probably due to the lack of fine structure information provided by the implant (Zeng, 2002), which is important for pitch perception, cuing place of articulation, voicing and tone quality (Rosen, 1992; Schauwers et al., 2012). Because of this, the CI is not able to effectively separate the different aspects of music such as melody and harmony, creating a listening experience without many of the subtleties and complexities intended by the composer or artist. The perception of these aspects of music was a key component in the development of the chord discrimination test, described in chapters 3 and 4.

6.1.2 Parameters of musical chords which affect pitch perception

Musical chords are a fundamental component of Western music, and a small number of previous studies have made use of their changeable attributes to examine pitch perception for CI users (Vongpaisal et al., 2006; Penninger, 2013, 2014). Taking these studies as a model, chapter 3 described a pilot study utilising psychophysical measurements of pitch discrimination to examine a number of different parameters of chords. The results of this pilot study informed a decision about which parameters to use in the main study described in chapter 4. The impacts of these different parameters are detailed below.

***Presentation of chords**:* In the pilot study, there was a significant main effect of the presentation of the chords, with participants performing better when chords were in the Simultaneous presentation rather than Sequential. It is likely that the three notes making up the chord were heard as a single tone when played simultaneously. Previous research has shown that CI users have difficulty identifying the number of tones presented when listening to acoustic stimuli, and report that they hear two or three simultaneous tones as a single tone (Donnelly et al., 2009). Additionally, CI users have difficulty in identifying the changing note in a melodic sequence (Pressnitzer et al., 2005). It is therefore not surprising that in the present research, participants found it easier to identify the changed chord with stimuli in the Simultaneous condition.

A possible limitation of this factor was the fact that examining differences in pitch perception between the Simultaneous and Sequential presentation of chords was complicated by the comparative lengths of the two types of stimuli. Simultaneous stimuli lasted only 0.5 seconds, whereas Sequential stimuli consisted of five 0.5 second tones in sequence, with 0.5 seconds of silence between each tone, making a 4.5 second sequence. Many participants reported a difficulty in recollecting the first stimulus after reaching the final (third) stimulus in the set. It is therefore difficult to know whether the better performance on the Simultaneous stimuli is due to the ease of remembering all three stimuli, rather than any benefit attained from the simultaneity of the presentation. A possible resolution of this issue for future use of the Chord Discrimination Test would be to run it alongside a test of auditory memory, to examine any effects it may have on this test.

***Chord root**:* There was no significant effect seen of the Chord Root factor in the pilot study, but this was confounded by the fact that notes were spread over several octaves. This was accounted for in the main study by keeping all notes of the chords within one octave. Better performance was seen in the main study when identifying the changing note in chords with a chord root of C5. Overall scores for the C5 Chord Root also correlated with overall VCV scores. The C5 octave covers frequencies which correspond to the first formant of many spoken vowels, which is important for speech recognition (Catford, 2001). The higher scores in the C5 octave may therefore be a result of the focus on speech perception in CI sound processing strategies and rehabilitation.

***Octave span**:* In the pilot study, an Octave Span condition was included to counter the effects of current spread. However, spreading the notes over several octaves did not provide any useful information, and served to confound the results when looking at the effect of using different chord roots. The pilot study showed a significantly better performance when chords were presented within a single octave, compared to three octaves. Therefore, in the main study, the Octave Span factor was eliminated, and chords were all presented with notes within a single octave.

***Chord change**:* The chord changes of Major-Minor and Major-Augmented were used in the pilot study to emulate the protocol of Vongpaisal et al. (2006). No significant effect of Chord Change was seen in this study, although scores from participants identifying the Major-Augmented change had a wider distribution with higher top scores. The note difference between a Major and Minor chord, or a Major and Augmented chord, is only one semitone. In the main study, the difference between the two chords was extended to two and three semitones. In this study, there was a significant difference when the top notes changed, following the pattern of a Major-Augmented change. To account for this results on the basis of hierarchy of tones (Krumhansl & Cuddy, 2010) or the particular qualities of the augmented chord, one would have expected a significant result in the pilot study as well as the main study. Therefore, this result is most likely due to the fact that the change of the top note of the chord may be perceptually more prominent, but the one semitone change used in the pilot study was too difficult for most CI users to discern.

***Semitone difference**:* Although some CI users were able to discern a one semitone difference between chords, the version of the Chord Discrimination Test in the pilot study was overall very difficult for the participants, with many performing at chance. This is in keeping with previous studies of CI users' pitch perception, which found that CI users had difficulty in identifying a pitch change of one semitone (Gfeller et al., 2002; Sucher & McDermott, 2007; Galvin et al., 2007). In the main study, results improved significantly with increasing numbers of semitone difference between the chords. This showed that despite the complexity of the stimuli used in the Chord Discrimination Test, it was still within the capabilities of CI users to perform to task.

***Device**:* Better performance on the Chord Discrimination Test was seen by participants with MED-EL devices. However, one limitation of both the pilot and main studies is the fact that only 18 participants were recruited. While great care was taken to ensure that this sample consisted of an equal number of participants from each of the three main cochlear implant manufacturers, it is still too small a sample to be able to make strong conclusions from. Additionally, other participant factors such as age at onset of deafness made it difficult to draw conclusions based on device manufacturer alone. Future testing with an increased number of participants, and looking separately at pre- and post- lingually deafened participants, would counteract the limitations of this present study in regards to individual differences amongst participants, and provide more robust indication of differences between device types.

6.1.3 Complex tones in musical chords

Complex sounds are heard much more commonly in everyday life than pure tones, which are rarely heard. Previous studies showing complex tones more difficult to perceive than pure tones for CI users (Gfeller et al., 2002; Sucher & McDermott, 2007, Singh et al., 2009). In this study, there was no significant difference in performance between the Piano Simulation and Sinusoid tone conditions, which conflicts with the above findings but is in keeping with the results obtained by Donnelly et al. (2009). However, an effect of frequency range was seen. In the two higher Chord Root conditions – C6 and C7, which corresponded to frequencies above 1 kHz - CI users were significantly better at identifying the changed chord in the Sinusoid tone condition than in the Piano simulation condition. This could be a result of higher frequencies being easier than lower frequencies in tasks using pure tones stimuli, which has been found in previous studies (Smith et al., 2002; Singh et al., 2009).

6.1.4 Relationship between musical chord perception and speech perception

As previously mentioned, the significant effect of the Chord Root factor, with overall scores peaking in the C5 region (covering 523 Hz – 988 Hz) is interesting to note alongside the correlation between overall scores for the C5 Chord Root and overall VCV scores, and may be a result of the focus on speech perception in CI sound processing strategies. In the pilot study, a significant correlation was seen between VCV scores and scores on the chord test in the one Octave condition. In the main study, there was a significant correlation between scores on the VCV test and Chord Discrimination scores in the Piano Simulation tone condition. These results both suggest that higher performing participants may have better perception of spectral information important for consonant recognition (Faulkner 2006; Donaldson & Kreft 2006) and are able to use the same capabilities in recognising pitch changes in complex stimuli. However, scores on the IHR sentences in noise test did not correlate with any scores on the Chord Discrimination Test, which conflicts with previous findings that speech in noise correlated to performance on pitch and music tasks for CI users (Gfeller et al., 2007); however, this study used spondees rather than sentences, which may be a more difficult task. The lack of correlation found in the present research may be due to the high amount of variability and individual differences seen between participants in this study. Additionally, this finding is in keeping with other research that has found the speech recognition is not a predictor of pitch perception (Gfeller et al., 2008).

6.1.5 Pitch perception in a musical context

Moderate negative correlations were seen between adaptive pitch ranking and chord test results in each octave range, but many participants who had difficulty in the chord test when the difference in the target chord was one semitone had no such problem when pitch ranking at one semitone, suggesting that pitch perception in a musical context presents a greater challenge than when listening to isolated pitches. This is in keeping with research by Pressnitzer et al. (2005), who found that CI users were unable to identify the changing note in the subsequent melody test, even when the change was greater than their previously determined pitch ranking thresholds. Other studies have shown that the complexity of the stimuli has a negative effect on CI users' ability to perceive changes in pitch (Gfeller et al., 2002; Sucher & McDermott, 2007, Singh et al., 2009).

6.1.6 Differences between pre- and post-lingually deafened CI users

A novel aspect of the research detailed in this thesis is the comparison between pre- and post-lingually deafened adults on both their objective pitch perception in musical contexts, and their subjective experience of music as CI users. In the present research, pre-lingually deafened participants performed significantly worse on the Chord Discrimination Test, but were much happier with their experience of music overall than post-lingually deafened participants. Pre-lingually deafened adults are considered non-traditional implant recipients, and typically do not receive the same benefit to their speech perception from their implant as post-lingually deafened adults (Wooi Teoh et al., 2004; Bosco et al., 2010). Despite this, subjective reports from pre-lingual CI users describe benefits, particularly in terms of their self-esteem (Bosco et al., 2010). This concurs with the present finding that objective measures of benefit from the CI do not give the full impression of the positive subjective impact pre-lingually deafened CI users can gain from their implant.

6.1.7 Musical chord discrimination in NH and NI children

Chapter 5 described the preliminary testing of the performance of both hearing impaired and normally hearing children on a portion of this test battery. A group of six and seven year old NH and HI took part in study using a section of the Chord Discrimination Test. The test was found to be suitable for use with children, who performed on average above chance on the task, despite many having a lower vocabulary age than their actual age.

It was shown that identifying small changes in musical chords was more challenging for HI children than for HI adults, with HI children performing generally just above chance. This is in keeping with previous findings that HI children are outperformed by NH children on pitch perception tasks (Looi & Radford, 2011; Edwards, 2013). These previous studies also found that children with CIs were outperformed by children with HAs and bimodal stimulation. The present research found no significant difference between the three HI groups; however, the participant numbers were very small.

The significant improvement seen in tests scores on the third of the initial three timepoints (carried out in July 2015) compared to the first timepoint (January 2015) suggests that the Chord Discrimination Test is sensitive to differences in pitch perception abilities over time, which supports its use as a pitch perception assessment in musical training programmes, which have been shown to have a beneficial effect on pitch perception abilities of HI children (Chen et al., 2010; Nardo et al., 2015).

A half-semitone condition was added to the Semitone Change factor at a later phase of the study. This was found to be significantly more difficult than identifying one, two or three semitones for all children. However, NH children performed above chance, and six of the eight HI children were above chance at the half-semitone task when the note change occurred in the top note of the chord. This suggests that some HI children that the potential for a finer degree of pitch perception than other studies have shown (Looi, 2014).

6.1.8 Comparison between adults and children with CIs

In the present research, adults were significantly better than children at performing the Chord Discrimination Test. This is contrary to previous research which has shown children with CIs outperform adults on pitch perception tasks (Looi, 2014). However, this result is complicated by the very low vocabulary age (average three years and eight months) of the children with CIs who participated in the study. It would be interesting to carry out a comparison of the performance of children at a later developmental stage with the performance of adults on the Chord Discrimination Test. Development of the ability to recognize changes in pitch and melody occurs early on in infancy (Carral et al., 2005; Plantinga & Trainor, 2009), but the pitch perception abilities of NH children does not approach that of adults by age 6 or 7 (Trainor and Trehub 1994; Trehub et al 1986), and performance on tasks relating to pitch perception has been shown to improve both with age and with experience of music (Lamont, 1998). Therefore, a more accurate comparison of the performance of children and adults on the Chord Discrimination Test can only be made if testing occurs with children at a more appropriate age.

6.2 Theoretical considerations

There are number of theoretical considerations relating to music psychology which were brought to light by the research described in this thesis. These concern the position of the changing note in the chord, and its availability on the diatonic scale.

Position of the changing note. The results of the Chord Discrimination Test showed that for adult listeners, a change in a chord was easier to determine when the top note changed than when the middle note changes, as long as the change was not limited to one semitone. This can be linked to work by Huron (1994), found that listeners were better able to identify voice entries in a polyphonic piece of music when they were outer voices (i.e., higher or lower in frequency than the rest of the voices present). The finding in the present study could therefore be further tested by creating a version of the chord test in which the bottom note of the chord changes, which was not done here. It would be predicted that a change in the bottom note of the chord would also be easier to detect than a change in the middle note.

Availability of notes on the diatonic scale. When the Chord Discrimination Test was carried out with NH children, there was a drop in performance when changing note was altered by two semitones, compared to one or three. These results suggest that there is an effect of the availability of the presented tones on the diatonic scale. Raising the top note of the chord by two semitones, or lowering the middle note of the chord by the same amount, means that the changes note remains within the diatonic scale. It has been theorized that intervals which keep within the diatonic scale are perceived as more consonant (Krumhansl, 1990), suggesting that for NH listeners, a higher level of consonance makes the change of chord more difficult to discern. This brings up the possibility of adapting the Chord Discrimination Test to further examine the relationship between results on the chord test and the relative consonance or dissonance of the intervals within the chord. It would be expected that NH listeners would perform better on the test where the changed note led to intervals with greater perceived dissonance, and worse when it led to intervals of greater perceived consonance.

6.3 Future directions

One important finding of this research was that a person's experience of music prior to deafness and implantation can have a significant effect on their enjoyment of music with the CI - even more than their performance on objective tests of pitch perception. Participants who were pre-lingually deafened, and therefore with no experience of music with normal hearing, were much more likely to report positively about their experience and enjoyment of music. When it comes to CI users' subjective experience of music, the present research would suggest that there is a need to focus on supporting post-lingually deafened adults through their expectations of music with a CI, and the potential for disappointment. Additionally, age at implantation is important for adults as well as children when it comes to the enjoyment of music, with those implanted before the age of 40 much more likely to spend time listening to music. Plant (2015) described a number of factors which can improve the music listening experience for adults CI users. These include the familiarity of the music, the availability of audio-visual cues, an open-minded approach, and the simplicity of the arrangements. The present research would suggest that more effort needs to be made by those involved in the support and care of post-lingually deafened adults into re-introducing and re-training newly implanted CI users in listening to music, perhaps taking these factors into account.

The Chord Discrimination Test devised in this research has multiple possible applications. As seen in chapter 5, it can be applicable for use in musical training programmes. Previous studies have shown that musical training programmes can have a positive impact on pitch discrimination (Vandali et al., 2015), melodic contour recognition (Galvin et al, 2007), timbre recognition (Driscoll, 2012) and enjoyment of music (Gfeller et al, 2001). Musical training has also been shown to be effective in children on improving pitch perception (Chen et al., 2010; Welch et al, 2015) and song recognition (Nardo et al., 2015). The Chord Discrimination Test has a great deal of scope for use as a test of pitch perception at various stages of training, as it was in the study described in chapter 5. Additionally, the test could be used as an element of the training itself. For example, children in such a training programme could undertake the Chord Discrimination Test at regular intervals over the school year, with periodic assessments of its impact on, for example, phonological processing, reading abilities, or perception of pitch in speech, all of which have been shown to benefit from musical training (Anvari et al., 2002; Forgeard et al., 2008; Moreno et al., 2009).

One novel aspect of the Chord Discrimination Test is that it has been shown to be appropriate for use with both children and adults. Music perception test batteries are more commonly created and tested with either adults in mind – such as the MuSIC perception test (Brockmeier et al., 2011) – or specifically for children, such as the Primary Measures of Musical Aptitude (PMMA) test (Gordon, 1980), or the Music in Children With Cochlear Implants (MCCI) test battery (Roy et al., 2014). This also gives the Chord Discrimination Test scope for use across a range of abilities, such as in children or adults with learning difficulties, for whom music can be very important as an aspect of education or therapy (Ockelford et al., 2002).

An advantage of the Chord Discrimination Test is that it can be modified in different ways in order to test different factors that may impact CI users' music listening experience. One possible adaptation for the Chord Discrimination Test would be to develop levels of difficulty for the test, starting for example with pure tones and large semitones differences between the chords. If participants reached a certain level of correct responses, such as 80% correct, they could move on to the next level up in difficulty. Stimuli would increase in complexity, and semitone difference would decrease, as the levels progressed. In this way, as wide as possible a range of ages and abilities can be tested using the one test battery. Another possible adaptation would be to expand the parameters which the Chord Discrimination Test assesses. In the research described in this thesis, a number of parameters were selected for study (presentation of chords, chord root, octave span, chord change, semitone difference and complex versus pure tones). There are however many other options for parameters which could be easily incorporated into this Chord Discrimination Test. For example, the test could be modified to present chords using a variety of real instruments, in order test perception of timbre, which is impaired in CI users (Gfeller et al., 1997; Looi, 2008).

There are possible applications for the Chord Discrimination Test in clinical audiological settings. For example, at the fitting of an CI, the CI users typically listen to a variety of different sounds and reports their impression of the sound to the audiologist, who uses this information to make a customised 'map' which defines how the electrodes are stimulated. Using the Chord Discrimination Test as this stage could allow for an early assessment of the CI users' pitch perception in different regions, allowing the potential of an improved map and the ability to reassess over time using the same test. Similarly, in CI rehabilitation, the Chord Discrimination Test could be used to identify frequency regions which are difficult for CI users and help to target their rehabilitation.

Finally, there is evidence that the Chord Discrimination Test could be used as an assessment of sensitivity to musical scales. This could make it appropriate for use in a number of contexts, such as assessing the effectiveness of musical instruction involving scales, or in assessments of music perception anomalies such as amusia.

6.4 Concluding remarks

Music is extremely important in many people's lives, and hearing impaired people are no exception to this. The Chord Discrimination Test piloted and developed in the studies detailed in this thesis has been shown to be a useful tool in providing information about CI users' pitch perception in musical contexts, and has great scope for potential use in musical training and assessments of pitch perception, both in academic and clinical settings. However, the research presented in this thesis suggests that concentrating on objective measures of pitch and music perception may not be the only way forward to improving CI users' overall experience of music. A greater understanding of the musical experience of a CI user can only be obtained by looking at the relationship between CI users' subjective experience of music, their objective performance on music perception tests, and the individual factors which may affect both of these.

References

ASA (1960) Acoustical Terminology SI, 1-1960. New York: American Standards Association.

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. Journal of experimental child psychology, 83(2), 111-130.

Arnoldner, C., Riss, D., Brunner, M., Durisin, M., Baumgartner, W. & Hamzavi, J. (2007). Speech and music perception with the new fine structure speech coding strategy: preliminary results. Acta Oto-Laryngologica, 127, 1298-1303.

Arora, K (2012) Cochlear implant stimulation rates and speech perception. In Ramakrishnan, S. (ed) Modern Speech Recognition Approaches with Case Studies. InTech Open Access Publishing.

Attneave, F. and Olson, R.K. (1971). Pitch as a medium: A new approach to psychophysical scaling. Am. J. Psychol 84, 147–166

Bakker, D. R., & Martin, F. H. (2015). Musical chords and emotion: Major and minor triads are processed for emotion. Cognitive, Affective, & Behavioral Neuroscience, 15(1), 15-31.

Battmer, R.D., Zilberman, Y., Haake, P. & Lenarz, T. (1999). Simultaneous Analog Stimulation (SAS) – Continuous Interleaved Sampler (CIS) pilot comparison study in Europe. Annals of Otology, Rhinology and Laryngology, 108 (4), 69-73.

Bibas, A., Xenellis, J., Michaels, L., Anagnostopoulou, S., Ferekidis, E., & Wright, A. (2008) Temporal bone study of development of the organ of Corti: correlation between auditory function and anatomical structure. Journal of Largngology and Otology. 122 (4) 336-342

Bilger, R., Hopkinson, M., Payne, S., Vega, W.,1977. Evaluation of subjects presently fitted with implanted auditory prosthesis. Annals of Otology, Rhynology, and Laryngology, 86/3 Part 2, Supp!. 38

Bloom, L. (1993). Language acquisition and the power of expression. In H. L. Roitblat, L. M. Herman & P. E. Nachtigall (Eds.), Language and communication: comparative perspectives. Hillsdale, NJ: Erlbaum

Boeckmann-Barthel, M., Ziese, M., Rostalski, D., Arens, C., & Verhey, J. L. (2013). Melody and chord discrimination of cochlear implant users in different pitch ranges. Cochlear implants international, 14(5), 246-251.

Bosco, E., Nicastri, M., Ballantyne, D., Mancini, P., D'Agosta, L., Traisci, G., & Filipo, R. (2013). Long-term evaluation of prelingually deaf subjects implanted during adolescence and adulthood. Cochlear implants international.

Botros, A. (2001) Frequency to musical note converter, Internet www page at URL: http://newt.phys.unsw.edu.au/music/note/ (accessed 15/12/14)

Bowling, D. L. (2013). A vocal basis for the affective character of musical mode in melody. Frontiers in psychology, 4.

Brendel, M., Buechner, A., Krueger, B., Frohne-Buechner, C. & Lenarz, T. (2008). Evaluation of the Harmony sound processor in combination with the speech coding strategy HiRes 120. Otology and Neurotology, 29, 199-202.

Brockmeier, S. J., Fitzgerald, D., Searle, O., Fitzgerald, H., Grasmeder, M., Hilbig, S., ... & Arnold, W. (2011). The MuSIC perception test: a novel battery for testing music perception of cochlear implant users. Cochlear implants international, 12(1), 10-20.

Burkholder, J.P., Grout, D.J., & Palisca, C.V. (2010). A History of Western Music. New York, London: Norton, W. W. & Company, Inc.

Burns, N., & Grove, S.K. (1997). The practice of nursing research conduct, critique and utilization. Philadelphia: W.B. Saunders and co.

Busch, R. (1986). On the Horizontal and Vertical Presentation of Musical Ideas and on Musical Space (II). Tempo (New Series), 3(156), 7-15.

Carr, K. W., White-Schwoch, T., Tierney, A. T., Strait, D. L., & Kraus, N. (2014). Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. Proceedings of the National Academy of Sciences, 111(40), 14559-14564.

Carral, V., Huotilainen, M., Ruusuvirta, T., Fellman, V., Naatanen, R., & Escera, C. (2005) A kind of auditory ‘primitive intelligence’ already present at birth. European Journal of Neuroscience. 21(11) 3201-3204

Catford, J.C. (2001) A Practical Introduction to Phonetics (2nd edn.). Oxford: Oxford University Press.

Chen, J.K.C., Chuang, A.Y.C., McMahon, C., Hsieh, J.C., Tung, T.H. & Li, L.P.H. (2010). Music Training Improves Pitch Perception in Prelingually Deafened Children With Cochlear Implants. Pediatrics, 125, 793-800.

Cheveigne, A. (2006). Pitch Perception Models. In: Plack, C. J., Oxenham, A. J., & Fay, R. R. (Eds). (2006) Pitch:neural coding and perception (Vol. 24). Springer Science & Business Media, pp 169-235

Clark, G., 1987. The University of Melbourne-Nucleus multi-electrode cochlear implant. Adv. Oto-Rhino-Laryngol., 38: 1-189.

Cohen, A.J. (2005). Music cognition: defining constraints on musical communication. In: Miell, D., MacDonald, R., & Hargreaves, D.J. (eds) Musical Communication. Oxford: Oxford University Press.

Conway, C. M., Pisoni, D. B., & Kronenberger, W. G. (2009). The importance of sound for cognitive sequencing abilities the auditory scaffolding hypothesis. Current Directions in Psychological Science, 18(5), 275-279.

Cook, N. D., & Fujisawa, T. X. (2006). The psychophysics of harmony perception: Harmony is a three-tone phenomenon.

Crowder, R. G. (1984). Perception of the major/minor distinction: I. Historical and theoretical foundations. Psychomusicology: A Journal of Research in Music Cognition, 4(1-2), 3.

Dallos, P. (1996). Overview: Cochlear neurobiology. In P. Dallos, A. N. Popper, & R. R. Fay (Eds), The Cochlea (pp. 1-43). New York: Srpinger.

Deutsch, D. (1982). The processing of pitch combinations. In D. Deutsch (Ed.), The psychology of music. New York: Academic Press, pp. 271-316.

Deutsch, D. (1986). Auditory pattern recognition. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), Handbook of perception and human performance: Vol. II. Cognitive processes and performance. New York: Wiley Interscience.

Deutsch, D (1999). The processing of pitch combinations. In Deutsch, D. (ed) The Psychology of Music (2nd ed). San Diego: Academic Press.

Di Nardo, W. Schinaia, L., Anzivino, R., De Corso, E., Ciacciarelli, A., & Paludetti, G. (2015). Musical training software for children with cochlear implants. Acta Otorhinolaryngologica Italica, 35(4), 249.

Donaldson, G.S., Kreft, H.A., & Litvak, L. (2005). Place-pitch discrimination of single- versus dual-electrode stimuli by cochlear implant users**.** Journal of the Acoustical Society of America, 118 (2), 623-625.

Donaldson, G. S., & Nelson, D. A. (2000). Place-pitch sensitivity and its relation to consonant recognition by cochlear implant listeners using the MPEAK and

SPEAK speech processing strategies. The Journal of the Acoustical Society of America, 107(3), 1645-1658.

Donnelly, P. J., Guo, B. Z., & Limb, C. J. (2009). Perceptual fusion of polyphonic pitch in cochlear implant users. The Journal of the Acoustical Society of America, 126(5), EL128-EL133.

Dorman, M.F., Loizou, P.C., & Rainey, D. (1997). Speech intelligibility as a function of the number of channels of stimulation for signal processors using sine-wave and noise-band outputs. Journal of the Acoustical Society of America, 102, 2403-2411.

Dorman, M. F., Loizou, P. C., & Rainey, D. (1997). Simulating the effect of cochlear-implant electrode insertion depth on speech understanding. The Journal of the Acoustical Society of America, 102(5), 2993-2996.

Drennan, W. R., & Rubinstein, J. T. (2008). Music perception in cochlear implant users and its relationship with psychophysical capabilities. Journal of rehabilitation research and development, 45(5), 779.

Driscoll, V. D., Oleson, J., Jiang, D., & Gfeller, K. (2009). Effects of training on recognition of musical instruments presented through cochlear implant simulations. Journal of the American Academy of Audiology, 20(1), 71.

Edwards, S. (2013). Pitch Perception, Production and Musical Development of Hearing Impaired Children. Doctoral thesis, UCL (University College London).

Faulkner, A. (2006). The auditory processing of speech. In Luxon, L, Furman, J.M, Martini, A & Stephens, S.D.G. (eds) A Textbook of Audiological Medicine: Clinical Aspects of Hearing and Balance. Martin Dunitz, London.

Finley, C. C., & Skinner, M. W. (2008). Role of electrode placement as a contributor to variability in cochlear implant outcomes. Otology & neurotology: official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology, 29(7), 920.

Firszt, J.B., Koch, D.B., Downing, M.& Litvak, L. (2007). Current steering creates additional pitch percepts in adult cochlear implant recipients. Otology and Neurotology, 28, 629-636.

Firszt, J.B., Holden, L.K., Reeder, R.M. & Skinner, M.W. (2009). Speech recognition in cochlear implant recipients: comparison of standard HiRes and HiRes 120 sound processing. Otology and Neurotology, 30, 146-152.

Fishman, Y. I., Volkov, I. O., Noh, M. D., Garell, C., Bakken, H., Arezzo, J. C., & Steinschnieder, M. (2001). Consonance and dissonance of musical chords: Neural correlates in auditory cortex of monkeys and humans. Journal of Neurophysiology, 86, 2761–2788.

Forgeard, M., Schlaug, G., Norton, A., Rosam, C., Iyengar, U., & Winner, E. (2008). The relation between music and phonological processing in normal-reading children and children with dyslexia. Music Perception: An Interdisciplinary Journal, 25(4), 383-390.

Frederigue-Lopes, N. B., Bevilacqua, M. C., & Costa, O. A. (2015, February). Munich Music Questionnaire: adaptation into Brazilian Portuguese and application in cochlear implant users. In CoDAS (Vol. 27, No. 1, pp. 13-20). Sociedade Brasileira de Fonoaudiologia.

Friesen, L.M., Shannon, R.V., Baskent, D., & Wang, X. (2001) Speech recognition in noise as a function of the number of spectral channels: Comparison of acoustic hearing and cochlear implants. Journal of the Acoustical Society of America, 110, 1150-1163.

Fu, Q. J., & Shannon, R. V. (2000). Effect of stimulation rate on phoneme recognition by Nucleus-22 cochlear implant listeners. The Journal of the Acoustical Society of America, 107(1), 589-597.

Fujita, S. & Ito, J. (1999). Ability of Nucleus cochlear implantees to recognise music. Annals of Otology, Rhinology and Laryngology, 108, 634-640.

Galvin III, J. J., Fu, Q. J., & Nogaki, G. (2007). Melodic contour identification by cochlear implant listeners. Ear and hearing, 28(3), 302.

Geurts, L., & Wouters, J. (2000). A concept for a research tool for experiments with cochlear implant users. The Journal of the Acoustical Society of America, 108(6), 2949-2956.

Gfeller, K., Woodworth, G., Robin, D. A., Witt, S., & Knutson, J. F. (1997). Perception of rhythmic and sequential pitch patterns by normally hearing adults and adult cochlear implant users. Ear and hearing, 18(3), 252-260.

Gfeller, K., Christ, A., Knutson, J.F., Witt, S., Murray, K.T. & Tyler, R.S. (2000). Musical backgrounds, listening habits, and aesthetic enjoyment of adult cochlear implant recipients. Journal of the American Academy of Audiology, 11, 390-406.

Gfeller K, Turner C, & Mehr M. (2002) Recognition of familiar melodies by adult cochlear implant recipients and normal-hearing adults. Cochlear Implants International, 3, 29-53.

Gfeller, K., Witt, S., Adamek, M., Mehr, M., Rogers, J., Stordahl, J., & Ringgenberg, S. (2002b) Effects of training on timbre recognition and appraisal by postlingually deafened cochlear implant recipients. Journal of the American Academy of Audiology, 13 (3), 132-145.

Gfeller, K., Turner, C., Oleson, J., Zhang, X., Gantz, B., Froman, R., & Olszewski, C. (2007). Accuracy of cochlear implant recipients on pitch perception, melody recognition, and speech reception in noise. Ear and hearing, 28(3), 412-423.

Gifford R, Shallop J, Peterson A. Speech recognition materials and ceiling effects: considerations forcochlear implant programs. Audiol. Neurotol. 2008; 13:193–205.

Gordon, E.E., (1980). Manual for the Primary Measures of Music Audition and the Intermediate Measures of Music Audiation. Chicago: G.I.A.

Green, T., Faulkner, A., & Rosen, S. (2004). Enhancing temporal cues to voice pitch in continuous interleaved sampling cochlear implants. The Journal of the Acoustical Society of America, 116(4), 2298-2310.

Hacker, M. J., & Ratcliff, R. (1979). A revised table of d’ for M-alternative forced choice. Attention, Perception, & Psychophysics, 26(2), 168-170.

Hevner, K. (1935). The affective character of the major and minor modes in music. The American Journal of Psychology, 47(1), 103-118.

Hochmair, I., Nopp, P., Jolly, C., Schmidt, M., Schößer, H., Garnham, C. & Anderson, I. (2006). MED-EL Cochlear Implants: State of the Art and a Glimpse Into the Future. Trends in Amplification, 10, 201-219.

Hoff, E (2005). Language Experience and Language Milestones During Early Childhood. In K. McCartney & D. Phillips (Eds). Blackwell Handbook of early childhood development: Blackwell Publishing.

Hopyan T, Gordon KA, Papsin BC. (2011) Identifying emotions in music through electrical hearing in deaf children using cochlear implants. Cochlear Implants International, 12(1):21-6.

Hopyan-Misakyan, T. M., Gordon, K. A., Dennis, M., & Papsin, B. C. (2009). Recognition of affective speech prosody and facial affect in deaf children with unilateral right cochlear implants. Child Neuropsychology, 15(2), 136-146.

Hunter, P. G., Schellenberg, E. G., & Stalinski, S. M. (2011). Liking and identifying emotionally expressive music: Age and gender differences. Journal of experimental child psychology, 110(1), 80-93.

Huron, D. (1989). Voice denumerability in polyphonic music of homogeneous timbres. Music Perception: An Interdisciplinary Journal, 6(4), 361-382.

Huron, D. (1991). Tonal consonance versus tonal fusion in polyphonic sonorities. Music Perception: An Interdisciplinary Journal, 9(2), 135-154.

Huron, D. (1994). Interval-class content in equally tempered pitch-class sets: Common scales exhibit optimum tonal consonance. Music Perception: An Interdisciplinary Journal, 11(3), 289-305.

Jackson, C.J. (2000). The pilot study. In Furnham, A. (ed), Designing and analysing questionnaires: a manual for health professionals and administrators, pp 137-150. London: Whurr.

Kim, S. J., Cho, Y. S., Kim, E. Y., & Yoo, G. E. (2015). Can young adolescents with cochlear implants perceive different timbral cues?. Cochlear implants international, 16(2), 61-68.

Klop, W. M. C., Briaire, J. J., Stiggelbout, A. M., & Frijns, J. H. (2007). Cochlear implant outcomes and quality of life in adults with prelingual deafness. The Laryngoscope, 117(11), 1982-1987.

Kong, Y.Y., Cruz, R., Jones, J.A. & Zeng, F.G. (2004) Music perception with temporal cues in acoustic and electric hearing. Ear and Hearing, 25(2), 173-185.

Krumhansl, C.L. (1990). Cognitive foundations of musical pitch. Oxford: Oxford University Press.

Krumhansl, C. L., & Cuddy, L. L. (2010). A theory of tonal hierarchies in music. In Music perception (pp. 51-87). Springer New York.

Kuhl, P., Williams, K., Lacerda, F., Stevens, K., & Lindblom, B. (1992) Linguistic experience alters phonetic perception in infants by 6 months of age. Science. 255 (5044) 606-608

Lamont, A. (1998) Music, Education, and the development of pitch perception: the role of context, age and musical experience. Psychology of Music, 26, 7-25

Lassaletta, L., Castro, A., Bastaricca, M., Perez-Mora, R., Herran, B., Sanz, L., Josefa de Sarria, m. & Gavilan, J. (2008). Changes in listening habits and quality of musical sound after cochlear implantation. Otolaryngology-Head and Neck Surgery, 138, 363-367.

Leal, M.C., Shin, Y.J., Laborde, M.L., Lugardon, S., Andrieu, S., Deguine, O. & Fraysse, B. (2003). Music perception in adult cochlear implant recipients. Acta Oto-Laryngologica, 00, 1-11.

Licklider, J. C. R. (1956), "Auditory Frequency Analysis", in Information Theory, ed. by C. Cherry (Academic Press, New York).

Lin, Y. S., Lu, H. P., Hung, S. C., & Chang, C. P. (2009). Lexical tone identification and consonant recognition in acoustic simulations of cochlear implants. Acta oto-laryngologica, 129(6), 630-637.

Loizou, P.C. (1999). Signal processing techniques for cochlear implants. IEEE Engineering in Medicine and Biology, May/June 1999, 34-46.

Loizou, P.C., Stickney, G., Mishra, L. & Assman, P. (2003). Comparison of Speech Processing Strategies Used in the Clarion Implant Processor. Ear and Hearing, 24 (1), 12 – 19

Looi, V. (2008). The effect of cochlear implantation on music perception. A review. Otorinolaringologia, 58, 169-90.

Looi, V., McDermott, H., McKay, C., & Hickson, L. (2008). Music perception of cochlear implant users compared with that of hearing aid users. Ear and hearing, 29(3), 421-434.

Looi, V., McDermott, H., McKay, C., & Hickson, L. (2008b). The effect of cochlear implantation on music perception by adults with usable pre-operative acoustic hearing. International journal of audiology, 47(5), 257-268.

Looi, V., & Radford, C. J. (2011). A comparison of the speech recognition and pitch ranking abilities of children using a unilateral cochlear implant, bimodal stimulation or bilateral hearing aids. International journal of pediatric otorhinolaryngology, 75(4), 472-482.

Looi, V., & She, J. (2010). Music perception of cochlear implant users: a questionnaire, and its implications for a music training program. International Journal of Audiology, 49(2), 116-128.

Looi, V. (2014). Comparisons of the pitch perception abilities of adults and children using cochlear implants or hearing aids. Cochlear implants international, 15(sup1), S14-S16.

Lynch, M. P., & Eilers, R. E. (1991). Children's perception of native and nonnative musical scales. Music Perception: An Interdisciplinary Journal, 9(1), 121-131.

Magnussen, L. (2011). Comparison of the fine structure processing (FSP) strategy and the CIS strategy used in the Med-El cochlear implant system: Speech intelligibility and music sound quality. International Journal of Audiology, 50, 279-287.

Mäki-Torkko, E. M., Vestergren, S., Harder, H., & Lyxell, B. (2015). From isolation and dependence to autonomy–expectations before and experiences after cochlear implantation in adult cochlear implant users and their significant others. Disability and rehabilitation, 37(6), 541-547.

Mazzeschi, A. (2015). Exploring perception, learning and memory in a prodigious musical savant through comparison with other savants and ‘neurotypical’ musicians with absolute pitch. Doctoral Thesis, UCL, Institute of Education.

McDermott, H. J., and McKay, C. M. (1994). Pitch ranking with nonsimultaneous dual-electrode electrical stimulation of the cochlea. Journal of the Acoustical Society of America, 96, 155–162.

McDermott, H.J. (2004). Music perception with cochlear implants: A review. Trends in Amplification, 8(2), 49-82.

Micheyl, C., Delhommeau, K., Perrot, X., & Oxenham, A. J. (2006). Influence of musical and psychoacoustical training on pitch discrimination. Hearing research, 219(1), 36-47.

Miller, G.A. (1956). The magical number seven plus or minus two: Some limits on our capacity for processing information. Psychological Review, 63, 81-97.

Mirza, S., Douglas, S.A., Lindsey, P., Hildreth, T. & Hawthorne, M. (2003). Appreciation of music in adult patients with cochlear implants: a patient questionnaire. Cochlear Implants International, 4(2), 85–95

Miyamoto, R. T., Kirk, K. I., Svirsky, M. A., & Sehgal, S. T. (1999). Communication skills in pediatric cochlear implant recipients. Acta oto-laryngologica, 119(2), 219-224.

Moore, B.C.J. (1997). An Introduction to the Psychology of Hearing, 4th ed. London: Academic Press Limited.

Moore, B. C., & Carlyon, R. P. (2005). Perception of pitch by people with cochlear hearing loss and by cochlear implant users. In Pitch (pp. 234-277). Springer New York.

Moreno, S., Marques, C., Santos, A., Santos, M., Castro, S. L., & Besson, M. (2009). Musical training influences linguistic abilities in 8-year-old children: more evidence for brain plasticity. Cerebral Cortex, 19(3), 712-723.

Nakata, T., Trehub, S. E., Mitani, C., Kanda, Y., Shibasaki, A., & Schellenberg, E. G. (2005). Music recognition by Japanese children with cochlear implants. Journal of physiological anthropology and applied human science, 24(1), 29-32.

National Institute on Deafness and Other Communication Disorders Fact Sheet: Cochlear Implants (National Institutes for Health Publication No. 11-4798, Updated March 2011)

Nie, K., Barco, A., & Zeng, F. G. (2006). Spectral and temporal cues in cochlear implant speech perception. Ear and hearing, 27(2), 208-217.

Ockelford, A. (2012). Applied Musicology: Using Zygonic Theory to Inform Music Education, Therapy and Psychology Research. Oxford: Oxford University Press.

Ockelford, A., Welch, G., & Zimmermann, S. (2002). Focus of Practice: Music Education for Pupils with Severe or Profound and Multiple Difficulties—Current Provision and Future Need. British Journal of Special Education, 29(4), 178-182.

Ohgushi K, Hatoh T (1991) in Proceedings of the Ninth International Symposium on Hearing: Auditory Physiology and Perception, Perception of the musical pitch of high frequency tones, eds Cazals Y, Demany L, Horner K (Pergamon, Oxford).

Owens, E., Kessler, D.K., Raggio, M. & Schubert, E.D. (1985). Analysis and revision of the Minimal Auditory Capabilities (MAC) battery. Ear and Hearing, 6, 286-287.

Parncutt, R. (2012). Harmony: A psychoacoustical approach (Vol. 19). Springer Science & Business Media.

Patel, A. D. (2011). Why would musical training benefit the neural encoding of speech? The OPERA hypothesis. The relationship between music and language, 195.

Penninger, R. T., Limb, C. J., Vermeire, K., Leman, M., & Dhooge, I. (2013). Experimental assessment of polyphonic tones with cochlear implants. Otology & Neurotology, 34(7), 1267-1271.

Penninger, R. T., Kludt, E., Limb, C. J., Leman, M., Dhooge, I., & Buechner, A. (2014). Perception of Polyphony With Cochlear Implants for 2 and 3 Simultaneous Pitches. Otology & Neurotology, 35(3), 431-436.

Peretz, I., Gagnon, L., & Bouchard, B. (1998). Music and emotion: perceptual determinants, immediacy, and isolation after brain damage. Cognition, 68(2), 111-141.

Peretz, I., Ayotte, J., Zatorre, R. J., Mehler, J., Ahad, P., Penhune, V. B., & Jutras, B. (2002). Congenital amusia: a disorder of fine-grained pitch discrimination. Neuron, 33(2), 185-191.

Plack, C. J., Oxenham, A. J., & Fay, R. R. (Eds). (2006) Pitch:neural coding and perception (Vol. 24). Springer Science & Business Media.

Plant, G. (2015). Musical FAVORS: Reintroducing music to adult cochlear implant users. Cochlear implants international, 16(sup3), S5-S12.

Plantinga, J. & Trainor, L (2009) Melody recognition by two-month-old infants. Journal of the Acoustical Society of America. 125 (2), EL58-EL62

Pressnitzer, D., Bestel, J., & Fraysse, B. (2005). Music to electric ears: pitch and timbre perception by cochlear implant patients. Annals of the New York Academy of Sciences, 1060(1), 343-345.

Rader, E. (2010). Use Music Theory Intervals To Play By Ear. Retrieved 21.08.16 from http://www.piano-lessons-made-simple.com/music-theory-intervals.html

Ramos-Miguel, A., Ramos-Macías, A., Artiles, J. V., & Zaballos, M. T. P. (2015). The Effect of Reference Electrode Position in Cochlear Implants. J Int Adv Otol, 11(3), 222-8.

Rasch, R. A., & Plomp, R. (1982). The listener and the acoustic environment. The Psychology of Music, 2, 135-147.

Rattray, J., & Jones, M. C. (2007). Essential elements of questionnaire design and development. Journal of clinical nursing, 16(2), 234-243.

Roberts, L. (1986). Consonant judgments of musical chords by musicians and untrained listeners. Acustica, 62, 163-171.

Rosen, S. (1992). Temporal information in speech: acoustic, auditory and linguistic aspects. Philosophical Transactions of the Royal Society B: Biological Sciences, 336(1278), 367-373.

Rosen, S., Faulkner, A., & Wilkinson, L. (1999). Perceptual adaptation by normal listeners to upward shifts of spectral information in speech and its relevance for users of cochlear implants. Journal of the Acoustical Society of America, 106, 3629-3636.

Roy, A. T., Scattergood-Keepper, L., Carver, C., Jiradejvong, P., Butler, C., & Limb, C. J. (2014). Evaluation of a test battery to assess perception of music in children with cochlear implants. JAMA Otolaryngology–Head & Neck Surgery, 140(6), 540-547.

Saleh, S.M.I. (2013). The Efficacy of Fitting Cochlear Implants Based on Pitch Perception. Doctoral thesis, UCL (University College London).

Schauwers, K., Coene, M., Heeren, W., Del Bo, L., Pascu, A., Vaerenberg, B., & Govaerts, P. J. (2012). Perception of Pitch changes in hearing-impaired adults with aided and unaided hearing loss. Journal of Hearing Science, 2(3).

Schnupp, J., Nelken, I., & King, A. (2011) Auditory Neuroscience: Making Sense of Sound. Cambridge/London: The MIT Press.

Schulz E. & Kerber M. (1994). Music perception with the MED-EL implants. In: Hochmair-Desoyer IJ and Hochmair ES (eds). Advances in Cochlear Implants. Vienna: Manz, 326-332.

Science Buddies Staff. (2015, January 8). How to Make a Piano Sing. Retrieved May 12, 2016 from http://www.sciencebuddies.org/science-fair-projects/project_ideas/Music_p012.shtml

Shirvani, S., Jafari, Z., Sheibanizadeh, A., Zarandy, M. M., & Jalaie, S. (2014). Emotional perception of music in children with unilateral cochlear implants. Iranian journal of otorhinolaryngology, 26(77), 225.

Singh, S., Kong, Y. Y., & Zeng, F. G. (2009). Cochlear implant melody recognition as a function of melody frequency range, harmonicity, and number of electrodes. Ear and hearing, 30(2), 160.

Smith ZM, Delgutte B, & Oxenham AJ. (2002) Chimaeric sounds reveal dichotomies in auditory perception. Nature.;416:87-90.

Srinivasan, A.G., Padilla, M., Shannon, R.V., & Landsberger, D. M. (2013). Imrpoving speech perception in noise with current focussing in cochlear implant users. Hearing Research, 299, 29-36.

Stainsby, T.H., McDermott, H.J, McKay, C.M. & Clark, G.M. (1997). Preliminary results on spectral shape perception and discrimination of musical sounds by normal hearing subjects and cochlear implantees. Proceedings of the international computer music conference, Thessaloniki, Hellas, September 25-30.

Strait, D. L., & Kraus, N. (2014). Biological impact of auditory expertise across the life span: musicians as a model of auditory learning. Hearing research, 308, 109-121.

Sucher, C. M., & McDermott, H. J. (2007). Pitch ranking of complex tones by normally hearing subjects and cochlear implant users. Hearing Research, 230(1), 80-87.

Taylor, E. (1990). The AB Guide to Music Theory. London, UK: The Associated Board of the Royal Schools of Music (Publishing) Limited.

Townshend, B., Cotter, N., Van Compernolle, D., & White, R.L. (1987). Pitch perception by cochlear implant subjects. Journal of the Acoustical Society of America, 82, 106-115.

Trehub, S. E., Unyk, A. M., & Trainor, L. J. (1993). Maternal singing in cross-cultural perspective. Infant behavior and development, 16(3), 285-295.

Trehub, S. E., Cohen, A. J., Thorpe, L. A., & Morrongiello, B. A. (1986). Development of the perception of musical relations: Semitone and diatonic structure. Journal of Experimental Psychology: Human Perception and Performance, 12(3), 295.

Trehub, S. E., Schellenberg, E. G., & Kamenetsky, S. B. (1999). Infants' and adults' perception of scale structure. Journal of experimental psychology: Human perception and performance, 25(4), 965.

Tyler, R.S., Gfeller, K. & Mehr, M.A. (2000). A preliminary investigation comparing one and eight channels at fast and slow rates on music appraisal in adults with cochlear implants. Cochlear Implants International, 1(2), 82-87.

Vandali, A. E., Whitford, L. A., Plant, K. L., & Clark, G. M. (2000). Speech perception as a function of electrical stimulation rate: using the Nucleus 24 cochlear implant system. Ear and hearing, 21(6), 608-624.

Vandali, A. E., Sucher, C., Tsang, D. J., McKay, C. M., Chew, J. W., & McDermott, H. J. (2005). Pitch ranking ability of cochlear implant recipients: A comparison of sound-processing strategies. The Journal of the Acoustical Society of America, 117(5), 3126-3138.

Veekmans, K., Ressel, L., Mueller, J., Vischer, M., & Brockmeier, S. J. (2009). Comparison of music perception in bilateral and unilateral cochlear implant users and normal-hearing subjects. Audiology and Neurotology, 14(5), 315-326.

Verschuur, C. (2009). Modeling the effect of channel number and interaction on consonant recognition in a cochlear implant peak-picking strategy. Journal of the Acoustical Society of America, 125 (3), 1723-1736.

Vickers, D. A., Moore, B. C., & Baer, T. (2001). Effects of low-pass filtering on the intelligibility of speech in quiet for people with and without dead regions at high frequencies. The Journal of the Acoustical Society of America, 110(2), 1164-1175.

Volkova, A., Trehub, S. E., Schellenberg, E. G., Papsin, B. C., & Gordon, K. A. (2014). Children's identification of familiar songs from pitch and timing cues. Frontiers in psychology, 5.

Vongpaisal, T., Trehub, S.E., & Schellenberg, E.G. (2006). Song Recognition by Children and Adolescents With Cochlear Implants**.** Journal of Speech, Language, and Hearing Research; 49, 5. 1091-1103.

Ward, W.D. (1954). Subjective musical pitch. J. Acoust. Soc. Am 26, 369–380

Ward, J. (2006) The Student’s Guide to Cognitive Neuroscience. Hove: Psychology Press.

Welch, G. F., Saunders, J., Edwards, S., Palmer, Z., Himonides, E., Knight, J., Mahon, M., Griffin, S. & Vickers, D. A. (2015). Using singing to nurture children's hearing? A pilot study. Cochlear implants international, 16(sup3), S63-S70.

Wier, C. C., Jesteadt, W., and Green, D. M. (1977). “Frequency discrimination as a function of frequency and sensation level,” J. Acoust. Soc. Am. 61, 178–184.

Wightman, F. L. (1973). The pattern-transformation model of pitch. The Journal of the Acoustical Society of America, 54(2), 407-416.

Wilson, B. S., Lawson, D. T., Zerbi, M., & Finley, C. C. (1992). Speech processors for auditory prostheses: Virtual channel interleaved sampling (VCIS) processors—Initial studies with subject SR2. First Quarterly Progress Report, NIH project, (01).

Wilson, B.S., Lawson, D.T., Zerbi, M., Finley, C.C. & Wolford, R.D. (1995). New processing strategies in cochlear implantation. The American Journal of Otology, 16 (5), 669-675.

Wilson, B.S. (2004) Engineering design of cochlear implants. In: Zeng, F.G., Popper, A.N., Fay, R.R. (eds) Cochlear Implants: Auditory Prostheses and Electric Hearing. New York: Springer-Verlag

Wilson, B. S. (2006). Speech processing strategies. In: Cooper, H.R. & Craddock, L.C. (eds) Cochlear Implants: A Practical Guide (2nd ed.) London: Whurr Publishers.

Wilson, B.S. & Dorman, M.F. (2008). Cochlear Implants: A remarkable past and a brilliant future. Hearing Research, 242, 3-21.

Wilson, B. S., & Dorman, M. F. (2008b). Cochlear implants: current designs and future possibilities. J Rehabil Res Dev, 45(5), 695-730.

Wooi Teoh, S., Pisoni, D. B., & Miyamoto, R. T. (2004). Cochlear implantation in adults with prelingual deafness. Part I. Clinical results. The Laryngoscope, 114(9), 1536-1540.

Zeng, F.G. (2002). Temporal pitch in electric hearing. Hearing Research, 174, 101-106.

Zeng, F.G. (2004). Trends in cochlear implants. Trends in Amplification, 8 (1), 1-34.

Zeng, F.G., Rebscher, S., Harrison, W.V., Sun, X., & Feng, H. (2008). Cochlear implants: system design, integration and evaluation. IEEE Rev Biomed Eng., 1 (1), 115-142.

Zhu, Z., Tang, Q., Zeng, F. G., Guan, T., & Ye, D. (2012). Cochlear-implant spatial selectivity with monopolar, bipolar and tripolar stimulation. Hearing research, 283(1), 45-58.

Ziese, M., Stutzel, A., von Specht, H., Begall, K., Freigang, B., Sroka, S., & Nopp, P. (2000). Speech Understanding with the CIS and the n-of-m Strategy in the MED-EL COMBI 40+ System. ORL J Otorhinolaryngol Relat Spec 62, 321-329

Appendix: Music appreciation in cochlear implant users questionnaire

Music before hearing loss

If you had no hearing from birth, please move on to the next page (click 'Start' below).

1. Did you listen to music before losing your hearing?

Never	Rarely	Sometimes	Often	Very often
○	○	○	○	○

2. What type of music did you listen to?

☐ Classical
☐ Popular / rock
☐ Jazz
☐ Heavy metal
☐ Folk
☐ Country
☐ Others - what? ☐

3. How much did you enjoy listening to music?

Not at all	Slightly	Moderately	Much	Very Much
○	○	○	○	○

4. Did you play a musical instrument before losing your hearing?

○ Yes
○ No (go to question 6)

5. What instrument?

6. Did you sing before losing your hearing?

○ Yes
○ No

Music between loss of hearing and implantation

7. Did you listen to music between losing your hearing and implantation?

Never	Rarely	Occasionally	Often	Very often
○	○	○	○	○

8. What type of music did you listen to?

- ☐ Classical
- ☐ Popular / rock
- ☐ Jazz
- ☐ Heavy metal
- ☐ Folk
- ☐ Country
- ☐ Others - what?

9. How much did you enjoy listening to music?

Not at all	Slightly	Moderately	Much	Very Much
○	○	○	○	○

10. Did you play a musical instrument between hearing loss and implantation?

- ○ Yes
- ○ No (go to question 12)

11. What instrument?

12. Did you sing between hearing loss and implantation?

- ○ Yes
- ○ No

13. When your hearing loss was at its most pronounced prior to implantation, did you listen to music?

Never	Rarely	Sometimes	Often	Very often
○	○	○	○	○

Music with your cochlear implant

14. Do you listen to music now?

- ○ Yes
- ○ No - go to question 20

15. How soon after your cochlear implant was switched on were you listening to music?

16. Did it take time before you appreciated listening to music after implantation? If so how long?

17. How often do you listen to music now?

Never	Rarely	Sometimes	Often	Very often
○	○	○	○	○

18. What type of music do you listen to now?
    - ☐ Classical
    - ☐ Popular/Rock
    - ☐ Jazz
    - ☐ Heavy metal
    - ☐ Folk
    - ☐ Country
    - ☐ Others – what?

19. Which types of music do you feel are heard best after implantation?
    - ☐ Classical
    - ☐ Popular/Rock
    - ☐ Jazz
    - ☐ Heavy metal
    - ☐ Folk
    - ☐ Country
    - ☐ Others – what?

20. Compared to before going deaf how is listening to music now?
    - ○ Much worse
    - ○ Not quite as good
    - ○ Just the same
    - ○ A bit better
    - ○ Much better

21. How much do you enjoy listening to music now?

Not at all	Slightly	Somewhat	Much	Very much
○	○	○	○	○

22. In what way is listening to music now different?

23. Listening to music after your cochlear implant, are you:
    - ○ Very disappointed
    - ○ Disappointed
    - ○ No opinion
    - ○ Satisfied
    - ○ Very satisfied

24. Would you have had a cochlear implant just to be able to listen to music?
    - ○ Yes
    - ○ No

25. Do you play an instrument now, after your implant?
    - ○ Yes
    - ○ No (go to question 29)

26. What instrument?
    If this is different to the one in question 4, why?

27. How important is playing an instrument to you?
    - ○ Not at all
    - ○ Slightly important
    - ○ Of some importance
    - ○ Important
    - ○ Very important

28. Compared to before losing your hearing, how is playing an instrument now?

29. Do you sing now, after your implant?
    - ○ Yes

- ○ No (go to question 33)

30. Did you stop singing on losing your hearing, before your implant? If so when?

31. How important is singing to you?
    - ○ Not at all
    - ○ Slightly important
    - ○ Of some importance
    - ○ Important
    - ○ Very important

32. Compared to before losing your hearing, how is singing now?
    - ○ Much worse
    - ○ Not quite as good
    - ○ Just the same
    - ○ A bit better
    - ○ Much better

33. Do you have an occupation linked to music? If so what is your occupation and what effect has your cochlear implant made?

34. Do you have any comments or suggestions for other implant users?

About you

35. Are you male or female?
    - ○ Male
    - ○ Female

36. What is your current age?

37. What was your age when you received your cochlear implant?

38. At what age did you lose your hearing, and why, if known?

39. Please describe the make and model of your implant in as much detail as possible.

40. If you would like to be contacted about taking part in research at UCL's Ear Institute, please leave your name and email address below.