Music perception in bimodal cochlear implant users

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Abstract

While most cochlear implant users can perceive speech signals in quiet conditions very well, the perception of music is reported to be poor for most of them. In this thesis the perception of music in cochlear implant users was the main focus of the research.

It has been found that most cochlear implant users cannot perceive pitches of melodies which are very important to music perception. Another limitation in their perception of music was in the recognition of musical instruments or more generally the timbre of sounds. It is widely believed that the current technology of cochlear implants is suitable only for coding of speech signals and not music signals. There is a need to investigate the reasons for such poor perception of music. The poor perception of pitch is believed to be the main reason for poor music perception. A literature review showed that although pitch perception is not satisfactory in cochlear implant users, there is also a possibility of interference between the perception of pitch and other aspects like intensity and quality of sounds. Therefore in the rest of the research, the effects of these two aspects on the perception of pitch were investigated.

Three mechanisms were identified by which intensity could influence the perception of pitch (Current spreading, Electrode activation spreading, and Spectral spreading). Each mechanism was tested by inputting a specific stimulus type to the cochlear implant sound processor at two different intensity levels. Twelve bimodal cochlear implant users were the participants in this part of the research. The perceived pitch was quantified through a selected matched frequency value in the non-implanted ear (bimodal pitch matching). The results showed that the effect of intensity was observed when current spreading happened. Another finding of this research was that the perceived pitches due to stimulating different electrodes of the cochlear implants were lower than Greenwood's prediction. In addition, when spectral spreading was present in complex musical notes, the perceived pitch for low frequency was not significantly different from that of high

frequency. A wide range of frequency created a narrow range of different pitches in the cochlear implant. There were large individual differences among people. Some participants perceived lower pitch at higher intensity while others perceived higher pitch at higher intensity.

To test the effect of sound quality on perceived pitch all of the above mechanisms were tested twice: once with a pure tone as the matching sound in the non-implanted ear and again with a complex tone in the non-implanted ear. The matched frequencies using complex tones were significantly lower than their counterparts with pure tones. This showed that the type of sound had a significant effect on the perception of pitch. In addition when pitch matching was done in one ear (monaural pitch matching) and the types of both sounds in matching were completely similar, the participants could match pitch with more precision. This was another indication that sound quality had an effect on the perception of pitch. Monaural pitch matching in the implanted ear showed that the effect of intensity in the implanted ear was greater in comparison with monaural pitch matching in the non-implanted ear.

An earlier research study conducted by the author on a star performer indicated that current CIs can provide enough information for pitch perception of sounds from a single instrument when the listener is very familiar with that instrument. Bimodal cochlear implant users may experience different pitch percepts in implanted and non-implanted ears. The implication of this research is that a larger number of electrodes with narrower analysis filters in the sound processor could provide better fine structure information and improve pitch perception. The results suggest that more restricted current spreading could improve pitch perception as well.

Declaration

This is to certify that

i. the thesis comprises only my original work towards the PhD except where

indicated in the Preface below,

ii. due acknowledgement has been made in the text to all other material used,

iii. the thesis is less than 100,000 words in length

Preface

In an earlier study, I used the Clinical Assessment of Music Perception for Cochlear Implants (CAMP) test for doing experiments of Pitch Direction Discrimination, Melody Recognition and Timbre recognition. The F0 of notes in the Pitch Direction Discrimination test were modified to test low, middle and high frequencies.

CUNY sentences in noise were used to test the speech perception of the bimodal cochlear implant users in noise. This test was done under a program written by one of my colleagues Mr Kyle Slater.

My supervisor, Dr Jeremy Marozeau, wrote the programs for stimulus presentation in the experiments for absolute and relative pitch assessments in chapter 2 and pitch matching experiments in chapters 3 and 5.

Acknowledgments

I would like to express my sincere gratitude to my supervisors, Professor Peter Blamey, Dr Jeremy Marozeau and Dr Julia Sarant.

Professor Peter Blamey was my principal supervisor who provided continuous and endless support during my Ph.D study and research. His extensive knowledge and valuable experience in cochlear implant research helped me in all the steps of my research. Besides his brilliant scientific guidance, I am inspired by his character and patience which allowed me the room to work in my own way. I could not have imagined having a better supervisor for my PhD study.

The knowledge, scientific creativity and motivation of my second supervisor, Dr. Jeremy Marozeau, has been invaluable on both an academic and a personal level, for which I am extremely grateful. I thank him for his encouragement, insightful comments, and critical thinking.

I appreciate Dr Julia Sarant who was my third supervisor. This thesis would not have been possible without her help. Besides her precious comments, she always offered me the ways to improve my skills for research and to solve my problems.

My sponsor was Iran's Ministry of Health and Medical Education. I so appreciate my sponsor for financial support which allowed me to live in Australia and do my research at the University of Melbourne. In addition, I also received financial support from the Bionics Institute to present my research in various prestigious conferences. I appreciate the Institute and especially Professor Rob Shepherd, the Director of the Institute. I also thank the Royal Victorian Eye and Ear Hospital which granted us financial support to buy necessary equipment for this research. The Department of Audiology and Speech Pathology of the University of Melbourne also supported me with courses and financial and scientific assistance. I appreciate Professor Richard Dowell, the Head of the Department.

In my daily work I have been blessed with a friendly team of great colleagues and scientists. They always gave me very good comments. I learnt from them a lot. I would like to thank Professor Hugh McDermott, Professor Colette McKay and Dr Hamish Innes-Brown for their valuable comments on my work in our weekly meetings and for sharing their valuable experiences with me. I also thank Ms Marie Camilleri for her help in the melody segregation data collection. I appreciate Dr Gary Rance who agreed to be the member of the advisory group which supervised my progress and gave me good suggestions. I thank Mr Kyle Slater for his help in providing the program by which I administered the speech in noise test.

I sincerely appreciate the participants of my experiments who had extreme patience and commitment which let me do my experiments. They have been generous in terms of the time of participation in my experiments.

My special thanks go to my wife Roya for her understanding, patience and kindness and spiritual support. She always supported me with unending encouragement.

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Chapter 1: Literature Review

Music perception in cochlear implant users

Cochlear implants (CIs) have been a breakthrough for most people who could not take advantage of hearing aids. One of the factors which has contributed to successful outcomes is the improvement in the design of sound processors for CIs. As the main purpose of such improvement was to facilitate the perception of speech, sound processing strategiesare sometimes called speech processors. With advances in the design of CIs, the expectation of good sound quality from these devices is becoming higher and the perception of other types of sound signals is receiving more attention from researchers. One of these sound signals is music. Although there are some similarities between music and speech sounds, they have essential differences. Musical sounds have wider dynamic range and frequency spectrum than speech sounds (Chasin and Russo 2004, Chasin 2006). To perceive music satisfactorily, the amount of information which should be heard is much greater than for speech sounds. Another difference between speech and music is that some factors like musical training, cultural background and listening habits can influence the perception of music (Gfeller, Christ et al. 2000, Gfeller, Witt et al. 2002, Chen, Chuang et al. 2010). These differences limit the effectiveness of the sound processor for music and therefore most CI users are not satisfied with listening to music (McDermott and McKay 1997, Mirza, Douglas et al. 2003, Kong, Cruz et al. 2004, Nimmons, Kang et al. 2008, Singh, Kong et al. 2009, Ping, Yuan et al. 2012). Several studies have shown that the appreciation of music is decreased after implantation, especially in postlingually deafened people (Mirza, Douglas et al. 2003, Lassaletta, Castro et al. 2008, Migirov, Kronenberg et al. 2009). Before looking into how music is perceived by CI recipients in more detail, it is important to understand how a CI works.

How a cochlear implant works

Cochlear implant (CI) systems have two main components. One is a sound processor, including a microphone and battery, which is usually worn on the external ear. The other internal component includes the electrode array and an electronic receiver-stimulator package. The two components are coupled by an inductive link which enables power to be transferred from the sound processor into the internal device, thus obviating the need for a power source to be implanted. The same link also conveys data from the sound processor into the implant so that the required patterns of electric stimulation can be generated. Sounds are received by the external microphone, and delivered to the sound processor for analysis. Then, the signals are converted into digital form and divided into a number of frequency bands by means of a bank of band-pass filters. Each band-pass filter corresponds to an active electrode in the electrode array. The output from each of these band-pass filters is sent to a rectifier and is modulated with a train of biphasic electrical pulses. Finally these pulses are delivered to the corresponding electrode contacts for stimulation of the auditory neurons (Figure 1-1).

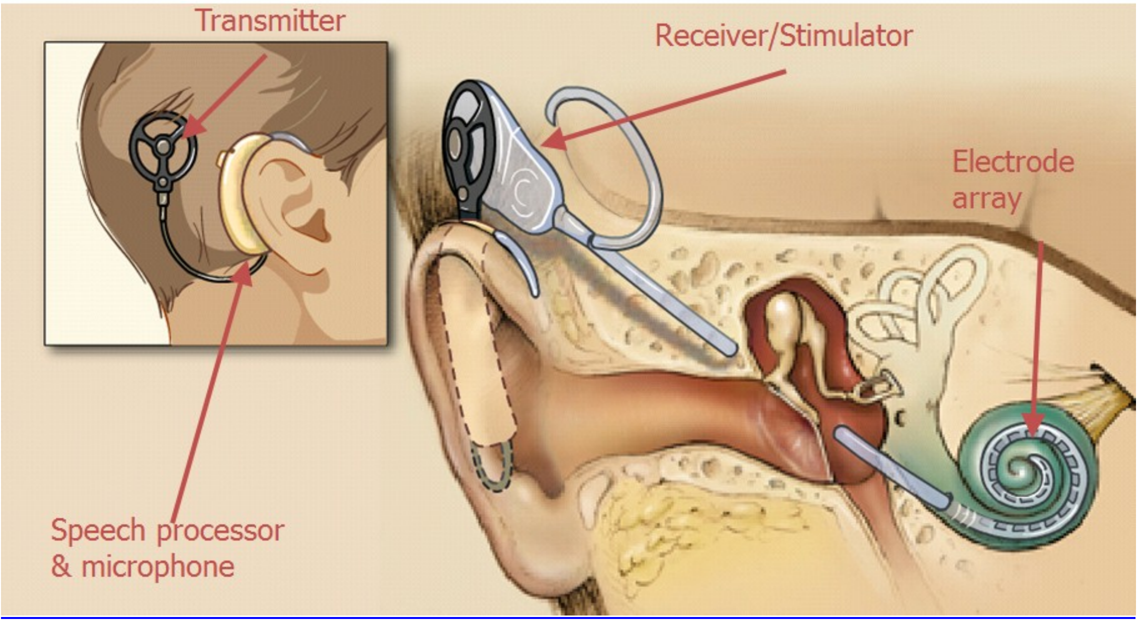

Figure 1-1: a cochlear implant and its components (MRC 2012)

Several manufacturers around the world make CIs (Cochlear, Advanced Bionics and MED-EL corporations are three of them). As well as different appearances, these products have technical differences as described in the following paragraphs:

I. Number of electrode contacts: the electrode arrays of different manufacturers have different numbers of electrode contacts. For example, there are 22 intracochlear electrode contacts in the Cochlear products, 16 electrode contacts in the products of Advanced Bionics and 12 electrode contacts in pairs in MED-EL CIs.

II. Electrode array: the electrode array can be straight or perimodiolar. Originally, the standard length electrodes were used with a straight shape structure that could only go approximately 1 turn into the cochlea. The perimodiolar array (Contour array) is expected to improve the efficacy of neural stimulation and be better for frequency resolution with more selective stimulation of target auditory nerve fibers because it lies very close to the spiral ganglions of the auditory neurons (Van Weert, Stokroos et al. 2005). Some products are available with both electrode array options.

III. Sound processing strategy: in some strategies, only the outputs of the band-pass filters with the largest peaks of energy are selected to stimulate their corresponding electrodes while in other strategies, the output of every band-pass filter is used to stimulate its corresponding electrode. Some manufacturers use one of these strategies while in some products it is optional to use either of these strategies.

It is believed that poor pitch perception in most CI users does not let them perceive music well. Pitch is defined as that attribute of auditory sensation by which sounds may be ordered on a musical scale (Plack, Oxenham et al. 2005). Pitch is the psychophysical correlate of the fundamental frequency of a complex sound. While the frequency of a sound is expressed in Hz, pitch is measured in units of mels. The pitch in mels is determined by scaling the pitch of a frequency to the pitch of 1000Hz. The pitch of a sound with the fundamental frequency of 1000 Hz is 1000 mels. If a sound has a pitch of 500 mels, its pitch is half of a sound with F0 of 1000 Hz. However in many cases, the judgment about the perception of pitch is derived from the fundamental frequency of a sound. For example when the pitches of two sounds are supposed to compare, their F0s are compared.

Pitch perception in CI users can be elicited in two ways: one way is by variation in the electric pulse rate which is called rate or temporal-pitch. Since it is perceived through the phase-locking of the firing of auditory neurons, it is sometimes called periodicity pitch. As the pulse rates used in current sound processors are high and constant, pitch does not vary by changing rate. The rate of the pulses is described as pulses per second (pps). There is also another temporal pitch mechanism in which the constant high rate pulses are amplitude-modulated by a signal at a lower frequency (modulator). Changing the frequency of the modulator usually results in a change in the perceived pitch. This mechanism of pitch perception is saturated above about 300 Hz modulation frequency (McDermott 2011).

Another way of changing the perceived pitch is by changing the place of stimulation. This is done by stimulating different electrodes and is known as place-pitch. The temporal pitch mechanism is only functional at low rates up to about 300 pps (Zeng 2002), with a few exceptions at higher rates (Tong and Clark 1985, Townshend, Cotter et al. 1987). The perception of pitch was measured in a musically trained CI user by varying the electrode place as well as the rate of stimulation (McDermott and McKay 1997). Although some musical pitch information can be provided by low rate temporal cues, electrode place-pitch information is the dominant cue for the pitch perception of a wide range of frequency. Nevertheless place cues do not provide strong perception of pitch (McDermott and McKay 1997). The relatively poor place-and temporal-pitch cues in CIs limit the ability to track the fundamental frequencies (F0) of musical notes in melodies (Laneau, Wouters et al. 2004, Kwon and van den Honert 2006). Since the ACE sound coding strategy uses a fixed high rate in the stimulation of the electrodes in electrode arrays, the perception of pitch is mediated by the place-pitch mechanism and by amplitude modulation. In addition, McDermott and Sucher (2006) concluded that a change of place of stimulation was in the same perceptual dimension as a change in acoustic frequency. CIs are limited in their electrode contacts and thus they stimulate a limited number of physical channels. However there have been some attempts to create virtual channels by stimulation of two channels simultaneously or with very brief time interval. This virtual channel can be between the two stimulated physical channels. This method is called current steering (Donaldson, Kreft et al. 2005)

Place-pitch mechanisms play a role in the pitch perception of normally hearing (NH) listeners. In NH people the auditory neurons which convey auditory information including pitch are attached to the base of the inner hair cells inside the cochlea. In NH listeners, each inner hair cell and its attached neurons are tuned to one frequency. The frequency at which each hair cell and its neurons are stimulated maximally is called the characteristic frequency (CF). The hair cells at different places along the cochlea are stimulated maximally by different CFs. This arrangement in responding to different sounds is called tonotopic organization. The tonotopic organisation means that the hair cells and the neurons attached to them at basal parts of cochlea respond best to high frequency sounds and the hair cells and the neurons attached to them at apical parts of cochlea respond to low frequency sounds. The auditory neurons are connected to the base of the hair cells via their dendrites. The cell bodies of auditory neurons form what is called the spiral ganglion in the modiolus, and the axons of the auditory neurons form the auditory nerve that connects the ear to the brainstem. The CF of each neuron for humans is described by the following formula which is known as Greenwood's function:

$$CF = 165.4\,(10^{2.1X/L} - 0.88)$$

In this formula, CF is calculated in Hz, X is the distance of the point for which the CF is being calculated on the basilar membrane from the apex of the cochlea and L is the total length of the cochlea in millimetres (Greenwood 1990). It is obvious that the length of the cochlea can affect the CF of the point which is being measured. The length of the cochlea in human beings varies from 32 to 35 mm (Von Békésy 1960, Otte, Schuknecht et al. 1978, Ulehlová, Voldrich et al. 1987). Figures 1-1 and 1-2 show the CFs of different points along the basilar membrane based on Greenwood's function for both lengths of 32 and 35 mm of the cochleae. CF is expressed in Hz or MIDI note number in this thesis in order to better understand the perceived pitch in the musical context of the research. MIDI stands for Musical Instrument Digital Interface and is a system in which each musical note is expressed by a unique number starting with note 0 for C-1 at 8.1758 Hz up to note 127 for G9 at 12,544 Hz. The CFs in figure 1-2 are shown in Hz and in figure 1-3 in MIDI numbers.

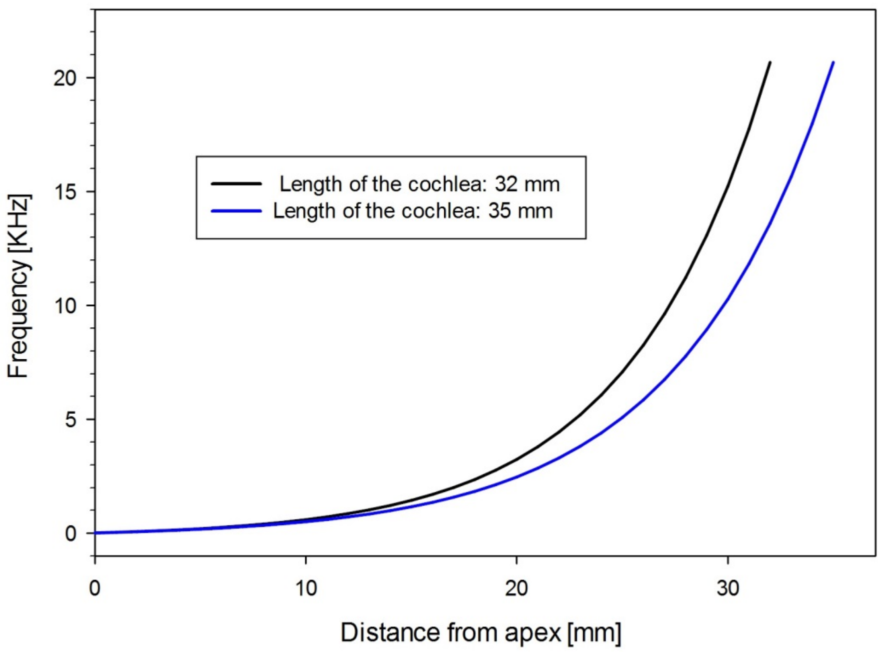

Figure 1-2: Greenwood's function of the CFs (in KHz) of different points along the cochleae with different lengths

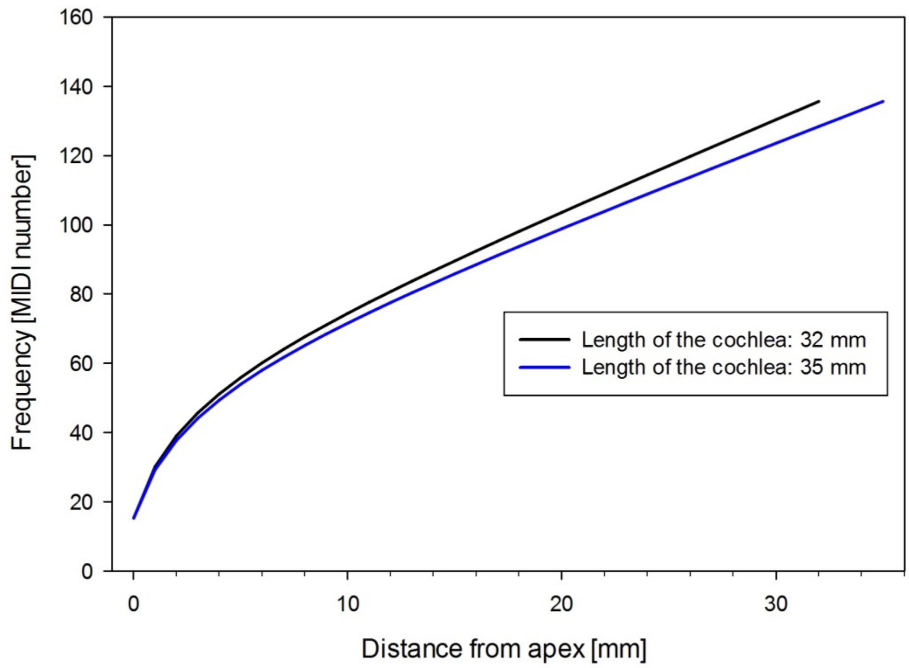

Figure 1-3: Greenwood's function of the CFs (in MIDI number) of different points along the cochleae with different lengths

Ideally the electrode contacts of the electrode arrays of a CI are manufactured so that they lie in close proximity to the auditory neurons while the hair cells may be dysfunctional or missing. In NH people, the stimulation of different places along the cochlea is translated into the firing of neurons and the tight attachment of the hair cells to the neurons secures the translation of the firing information of each place along the cochlea to its corresponding neurons. In contrast, there is no such attachment in CI users. To estimate the perceived pitches for CI electrodes Greenwood's function has also been used. The positions of the electrodes were compared to the position of spiral ganglion cells with specific characteristic frequencies since the target of the electrical stimulation is the spiral ganglion population rather than the hair cells. It has been shown that in the basal part of the cochlea, the nerve bundles from the hair cells lead directly into their cell bodies in the spiral ganglion in the modiolus, but in the middle and apical turns, the fibers travel a long way in the basal direction to reach their cell bodies in modiolus (Bredberg 1968, Glueckert, Pfaller et al. 2005). This means that in the middle and apical turns, the ganglion cell bodies are more basal than their corresponding hair cells, and consequently the perceived place pitch from electrical stimulation is lower than the CF predicted by the Greenwood formula based on electrode position (Blamey, Dooley et al. 1996).

Studies of the elements of music in CI users

While people are not unanimous about the definition of music, the most studied physical aspects of music are melody, harmony, rhythm and timbre. Many authors have tried to assess these elements of music in the population of CI users.

Melody and pitch

Melody is one of the outstanding features of each musical piece. By definition, melody is formed by a series of musical notes which occur in sequence and may be different in pitch. A melody is a combination of pitch and rhythm. Harmony is produced when two complementary notes sound simultaneously. Harmony is found in chords, or can be played along a main melody.

Rhythm

Rhythm is formed in the pattern of loudness and duration changes which happen on a short time scale from tens of milliseconds to several seconds. Rhythm reflects the temporal features of music in the order of seconds, while the fine scale temporal features that happen on the order of milliseconds are very important in the perception of pitch and timbre. Sometimes the rhythmic pattern of common tunes is distinctive enough to enable their identification without any melodic pitch information being available acoustically.

Timbre

Timbre or tone colour is a characteristic which allows the listener to distinguish between two musical instruments playing the same note with the same loudness. This aspect of music is derived from changes in intensity over time, spectral content and temporal changes in the spectrum (Moore 1998).

The combination and interactions of all the above-mentioned aspects constitute what we know as music. Each of these aspects has been the focus of research studies in people using CIs. Several musical tests have been developed to assess these musical aspects of perception in CI users as well. Although the perception of music is partly determined by the perception of its physical constituents described above, it is worth mentioning that the perception of these elements does not necessarily result in music appreciation (Looi, King et al. 2012).

Music perception studies on CI users

The perception of melody has been investigated with the presentation of excerpts from well-known songs and asking CI users to name the song. It is assumed that the perception of pitch would play a significant role in melody recognition. In one of these studies, Gfeller and colleagues in 2005 investigated the recognition of up to 45 familiar melodies, divided into three musical genres—pop, country and classical. Since familiarity with songs plays a role in melody recognition, all the participants were selected from native English-speaking adults culturally affiliated with the United States. The excerpts for the two former styles included lyrics whereas the excerpts for the classical genre were entirely instrumental (without lyrics). The mean recognition score of 15.6% for the 59 adults with CIs was significantly lower than the score of 54.7% for the 30 NH control subjects. When the melodies were presented with lyrics, CI users could recognise them significantly better than when the melodies were presented without lyric cues (Gfeller, Olszewski et al. 2005). This is not surprising because cochlear implant sound processors have been designed to code speech signals and, in this case, lyrics.

In another study, 12 familiar melodies were presented to 6 CI users with rhythm cues and then again with all the rhythmic information removed (Kong, Cruz et al. 2004). In the condition with rhythm, the mean score for the CI listeners was 63% correct, which was significantly lower than the score for a group of NH listeners. The NH listeners could recognize the melodies with nearly 100% accuracy with and without the inclusion of rhythmic cues. The CI listeners' mean score was only about 12% in the condition without rhythmic cues, which was close to chance level. These findings are similar to the results reported by other researchers who have studied melody recognition in CI users. This study revealed that whenever melody recognition was based purely on pitch information, CI users' performance dropped dramatically possibly due to poor pitch perception.

The above studies indicate that recognizing melody is possible for CI users based solely on lyrics and rhythmic cues and without enough pitch information. This is consistent with the findings of previous studies (Gfeller and Lansing 1991, Fujita and Ito 1999, Kong, Cruz et al. 2004). In the first study, the rhythm subtest of the Adapted Primary Measures of Musical Audition (PMMA) CI was used. This subset comprised pairs of short sequences of sounds, each recorded without change in pitch and timbre. The sequences in each pair were either identical or different in rhythm and they were presented randomly to the listener who was asked to determine whether the pair of sequences was the same or different. The chance level in this experiment was 50%. The CI users scored 88% on average with a range of 80% to 95%. Kong et al. (2004) compared the ability of normal-hearing and cochlear implant listeners to use temporal cues in three music perception tasks: tempo discrimination, rhythmic pattern identification, and melody identification. The CI listeners performed similarly to the NH listeners in tempo discrimination with 4-6 beats per minute. However, in rhythmic pattern identification, the CI listeners performed 5 to 25 percentage points poorer than the NH listeners. Without rhythmic cues, the CI users performed at chance level in the melody recognition test. With rhythmic cues, their performances increased significantly but their scores were still significantly lower than NH. While both temporal (rhythmic) and spectral (pitch) cues contributed to melody recognition, CI listeners mostly relied on the rhythmic cues for melody recognition. This indicates that although most studies have shown quite good rhythm recognition performance in CI users, their performance was still poorer than that of NH listeners. In addition, in another study, it was reported that CI users could recognise melodies with more distinct rhythmic cues more easily than melodies with less distinctive rhythmic cues. A possible reason for the good performance of CI users in rhythm recognition may be that the neural system of CI users locks tightly to timing information and they can hear temporal changes such as gaps and amplitude modulation almost as well as NH listeners (Shannon 1983, Honert and Stypulkowski 1984).

Timbre is encoded via the temporal envelope (onset characteristics in particular) and by spectral distribution of the harmonic frequencies of sound. While the temporal envelopes are fairly well preserved in CI processing, spectral information is reduced relative to the original acoustic signal (Kong, Mullangi et al. 2011). Consequently, timbre recognition in CI users is better than chance but not nearly as good as for NH listeners. This is clear from the results of many studies (Gfeller, Mehr et al. 2002, Gfeller, Witt et al. 2002, McDermott 2004, McDermott and Looi 2004). In addition, in CI users, unlike NH listeners, there was an overwhelming reliance on envelope cues for timbre judgments (Heng, Cantarero et al. 2011). This heavy reliance on envelope cues due to the weakness of CIs in coding fine spectral structure may account for most of the difficulties in timbre perception in CI users (Heng, Cantarero et al. 2011, Kong, Mullangi et al. 2011). Even if a CI could present the spectral fine structure, implant patients may not be able to perceive much of it (Zeng 2002) possibly due to degradation of phase-locking of the auditory nerve (Joris and Yin 1992). In addition, NH subjects more often mistake one instrument for another in the same instrument family (e.g., a trumpet for a trombone). Implant users, however, consistently show a more diffuse error pattern that is often unrelated to instrument family (Gfeller, Knutson et al. 1998, Gfeller, Witt et al. 2002).

In summary, NH subjects can use fine spectral and temporal information that helps define the pitch as well as the different colours or timbres of music. Therefore they can use these cues for timbre judgments when envelope information is not available (Smith, Delgutte et al. 2002, Heng, Cantarero et al. 2011). Electrical stimulation, on the other hand, cannot code such cues (Heng, Cantarero et al. 2011, Kong, Mullangi et al. 2011) and CI users do not have good perception of timbre. One strong point of electrical stimulation through CIs is that they are quite good at delivering rhythm. Rhythm can provide a sense of musical pleasure to a listener on its own, particularly to those deaf at birth or early in life who have no previous experience with melodies (Chen, Chuang et al. 2010).

In addition to the studies regarding physical aspects of music in CI users, the enjoyment of music after implantation has been investigated by several authors. Although most implant users reported substantially decreased music appreciation following implantation (Mirza, Douglas et al. 2003, Lassaletta, Castro et al. 2008, Migirov, Kronenberg et al. 2009), some users reported they still enjoyed listening to music after implantation (Lassaletta, Castro et al. 2008).

Another outstanding point about music perception in CI users is that in comparison with normally hearing listeners, CI users show a wide range of performance in nearly all aspects of music especially in pitch perception (Geurts and Wouters 2001, Gfeller, Turner et al. 2002 , Nimmons, Kang et al. 2008, Green, Faulkner et al. 2012). These wide ranges vary from very poor performance at chance level in pitch-related tasks to some exceptional performance comparable to NH listeners (Gfeller, Olszewski et al. 2005, Nimmons, Kang et al. 2008). It is not known why some people can obtain enough information through current CIs while others in a similar situation cannot perform well even in rhythm experiments that are reported to be easy for most CI users in most studies.

Tasks in music perception tests vary from very simple ones like detection to very difficult identification tasks. In the presence of the task variability and inter-listener capability, it is difficult to assess how well the current CI technology performs in the higher levels of music perception. Theoretically it is possible to test CI users with excellent performance with higher difficult levels of perception but practically there are not many exceptional CI users. If extensive musical experiments could be carried out on such CI users, the fundamental restriction of current CI technologies in coding music might be revealed.

Improving music perception with cochlear implants

The limitation of CIs is believed to stem from the limitations in their technical function and/or the ability of the impaired auditory system to extract enough information from the electric stimulation. Several methods have been used to improve music perception for CI users.

Music training

Although it is plausible that auditory training tailored for music perception would be beneficial to some CI users, it cannot solve some problems like poor spectral resolution and lack of the coding of temporal fine structure by current CIs. There is some published evidence that music training programs could improve the music perception of CI users, at least to a limited extent (Gfeller, Witt et al. 2000, Jayakody, Looi et al. 2012, Looi, King et al. 2012) (Chen, Chuang et al. 2010, Koşaner, Kilinc et al. 2012).

Bilateral CI implantation

Compared to unilateral cochlear implantation, there are benefits in using bilateral cochlear implantation for speech in quiet and in noise (Gantz, Tyler et al. 2002, Litovsky Ruth, Aaron Parkinson et al. 2006, Buss, Pillsbury et al. 2008, Ching, Massie et al. 2008, Koch, Soli et al. 2009, Jose 2012), localization accuracy (Neuman, Haravon et al. 2007, Grantham, Ashmead et al. 2008, Koch, Soli et al. 2009) and better experience in listening to music and easier recognition of melody and timbre (Veekmans, Ressel et al. 2009, Vecchiato, Maglione et al. 2012). This configuration can possibly assist with using bilateral advantages which include the head-shadow effect (Schafer, Amlani et al. 2007), binaural unmasking (Long, Carlyon et al. 2006, Van Deun, van Wieringen et al. 2009, Lu, Litovsky et al. 2011), binaural redundancy and binaural summation (Firszt 2008). The head-shadow effect relates to the attenuation, particularly of high-frequency sounds, that occurs when a signal directed at one ear must travel around the listener's head to reach the opposite ear. Binaural unmasking refers to the improvement in intelligibility under conditions of masking when a tone is presented out of phase rather than in phase to opposite ears. Binaural redundancy is the advantage obtained from receiving identical information about the signal in both ears (also referred to as diotic listening). Binaural summation is the sensation that a signal is perceptually louder when listening occurs with two ears relative to one. Overall, for people with bilateral implants, the influence of the head-shadow effect accounts for the majority of bilateral advantage whilst the contributions of binaural unmasking, binaural redundancy and binaural summation are relatively insignificant (Schleich, Nopp et al. 2004, Peters, Litovsky et al. 2007, Van Deun, van Wieringen et al. 2010). Veekmans, Ressel et al. (2009) have reported generally better perception and appreciation of music after receiving the second implant compared with only one CI. Easier adaptation and more motivation in listening to music with the second implant were suggested as the factors that could explain the improved perception in bilateral CI users. The participants of their study also reported benefits of the second implantation in recognising elements of music such as melody, rhythm, high and low frequencies and instrument timbre, whereas participants with unilateral CI only reported recognising rhythm. One possible explanation might be that with bilateral implantation the better ear is always captured. Another might be that there was more redundancy with two ears.

Bimodal hearing

As pitch perception is reported to be better in ears with residual hearing and most difficulties in music perception of CI users are due to a deficiency in pitch perception (Sucher and McDermott 2009, Straatman, Rietveld et al. 2010, McDermott 2011), a bimodal CI plus hearing aid configuration is possibly helpful. Some studies have reported binaural advantages for bimodal CI as well (Schafer, Amlani et al. 2007, Firszt, Reeder et al. 2008, Kokkinakis and Pak 2014). In the bimodal configuration, one ear is implanted and the other ear has enough residual hearing (mostly at low frequencies) to be fitted with a hearing aid. Sometimes there is some residual hearing in the implanted ear after implantation. If a sound signal is transmitted with both electric and acoustic hearing in the same ear, the configuration is called a hybrid CI. Bimodal and hybrid listening uses acoustic amplification to improve the low-frequency hearing while taking advantage of cochlear implant technology to restore access to high-frequency hearing. These configurations allow a user to benefit from the strengths of both devices. It is believed that when low-frequency residual hearing still exists, better pitch information and temporal fine structure are available than when there is no residual hearing in the non-implanted ear. (Kong, Stickney et al. 2005). In studies on hearing impaired people, it has been reported that when there was hearing loss in low frequency region, pitch perception was deteriorated while when hearing loss was restricted to high frequency, the perception of pitch was close to normal. It has been attributed to the presence of fine temporal information at low frequency.(Ghung, Hall et al. 2004, Schauwers, Coene et al. 2012). Better pitch perception and temporal fine structure can improve the ability of these patients to hear speech in noise (Kong, Stickney et al. 2005, Brown and Bacon 2009), and enjoy music (Fitzpatrick, Séguin et al. 2009).

In a study of 9 bimodal users, Sucher and McDermott (2009)reported that bimodal stimulation provided better performance on familiar melody recognition and complex sound identification than CI- and HA-alone conditions. In addition, subjective measures indicated that the participants preferred the bimodal condition when listening to music in comparison to CI- or HA-alone despite the fact there was no usable residual hearing in the non-implanted ear above 750 Hz. They concluded that acoustic and electric stimulation have differences in relative pitch, loudness, and timing and these mismatches between the two kinds of stimuli may result in suboptimal bimodal listening conditions. They recommended that if the two devices were modified somehow to make particular characteristics of electric and acoustic stimulation more similar or complementary, then bimodal stimulation would lead to even better results (Sucher and McDermott 2009). This is consistent with the results of earlier studies (Blamey, Dooley et al. 1996, Blamey, Dooley et al. 2000, Tyler, Parkinson et al. 2002).

Kong, Stickney et al. (2005) studied melody recognition without rhythmic cues in three ranges of frequency (low-mid-high) on five CI users with residual hearing in the non-implanted ear in three conditions: HA alone, CI alone and CI+HA. In the low-frequency melody condition, all melodies were within a frequency range from 104 (G#2) to 261 Hz (C4) whereas the mid-range (208 to 523 Hz) and high-range (414 to 1046 Hz) melodies were one and two octaves above the low-range melodies respectively. There was large variability in the results of all three conditions. The performance with combined hearing was determined by the non-implanted ear. This indicated that the acoustic hearing (through HAs) could provide fine structure cues at low frequencies which could improve melody recognition.

Looi and Radford (2011) tested pitch ranking of children using CI alone, bilateral HAs and bimodal CI users. There was also no significant difference between the pitch ranking scores of users of bimodal and users of a CI alone. However participants using only acoustic hearing (HA group) scored significantly higher than participants using electrical stimulation. It showed that the performance of children using electrical stimulation was significantly poorer than children using only acoustic stimulation.

In another study on children using CIs and HAs, Innes-Brown, Marozeau et al. (2013) tested rhythm, pitch and timbre instrument recognition in children with hearing impairments who have been using CIs or HAs. They showed that temporal cues could be used by the children not only for rhythm, but also for the recognition of some aspects of timbre.

Another study investigated the relationship between the hearing thresholds in the non-implanted ear and music perception (El Fata, James et al. 2009). This study was conducted with two aims. The first aim of the study was to evaluate the performance of fourteen bimodal users on the recognition of popular songs with and without lyrics in three conditions: bimodal, CI alone and HA alone. The second aim was to relate the participants' performance in music perception to their hearing thresholds in order to assess the possible benefit of bimodal stimulation. They divided their participants into two groups based on the median of the pure tone thresholds of 125, 250, 500 and 1000 Hz in their non-implanted ears. If the participants had a median hearing loss of 85 dB or less they were put in group 1 (with more residual hearing), otherwise they were in group 2 (with less residual hearing). They concluded that bimodal stimulation provided better perception of popular music, particularly for melody recognition when compared to CI and HA alone, but this was only true for individuals in group 1. If the median of the thresholds was worse than 85 dB (group 2), then bimodal stimulation was not significantly different from the CI alone condition. Nevertheless, there are other studies which show that residual hearing in the contralateral ear can help to make an improvement in the perception of music, regardless of the hearing thresholds (Kong, Stickney et al. 2005, Gifford and Dorman 2007, Sucher and McDermott 2009). Kong, Stickney et al. (2005) tested 3 sets of 12 melody items in a melody recognition experiment in CI-alone, HA-alone and HA+CI conditions while the rhythmic cues were removed from the items. In most cases they observed higher scores of melody recognition in HA-alone and HA+CI conditions. They ascribed higher scores to the salient pitch in low-frequency acoustic hearing. Sucher and McDermott (2009) examined the perception of music and sound quality by nine post-lingually deafened adult CI users in three conditions: CI-alone, HA-alone and HA+CI conditions. On average, bimodal stimulation provided the best results for music perception and perceived sound quality when compared with results obtained with electrical stimulation alone. Thus, for CI users with usable acoustic hearing, bimodal stimulation may be advantageous when listening to music and other non-speech sounds. This may occur because of increased redundancy or binaural advantages in some situations.

To investigate the difference between bilateral cochlear implantation and using residual hearing in the opposite ear, Cullington & Zeng (2011) recruited thirteen bilateral CI users and thirteen bimodal users to do some experiments including music perception. Their initial hypothesis was that bimodal stimulation (the combination of HA in one side and CI in the other ear) would result in better music perception than bilateral stimulation using binaural CIs. They used the Montreal Battery of Evaluation of Amusia (MBEA)(Peretz, Champod et al. 2003) as their test material. They noticed that the bimodal group performed better than the bilateral group on pitch related tasks but the difference was not statistically significant. They put forward four reasons for their results. Firstly, the bilateral CI group was not truly representative of CI users because their screening criteria selected only good CI users. Secondly, the MBEA has the disadvantage that the pitch subtests are too difficult for CI users. Therefore, it provides limited information about the subjects' pitch discrimination abilities. The difficulty of the test may explain the lack of difference in performance between the groups. Thirdly, they reasoned that the number of participants in the study was too small. Finally, the two devices were fitted with different fitting protocols by different practitioners (Cullington and Zeng 2011). The HA fitting protocol was not adjusted or balanced with the CI fitting protocol. Therefore, the fittings of the HAs and CIs were not supportive of each other and may have detracted from optimal use of both devices. The question of whether a patient would benefit more from a contralateral hearing aid or a second cochlear implant remained unanswered in the study due to the above-mentioned considerations. This study hypothesized that bimodal hearing could be more advantageous than bilateral implantation and indicated that acoustic hearing might provide improved low-frequency pitch in comparison with bilateral implantation which could only bring about binaural listening advantages. This hypothesis is supported by some previous studies (Gfeller, Olszewski et al. 2006, Nittrouer and Chapman 2009). Acoustic hearing can provide some helpful cues for music perception which bilateral implantation does not provide.

The beneficial effect of the addition of residual hearing in improvement of music perception in CI users was hypothesized in a study by Gfeller et al. in 2006 . They tested four hybrid CI recipients, 17 normally hearing adults, and 39 conventional CI recipients with open-set recognition of real-world songs presented with and without lyrics. They also tested 14 hybrid CI recipients, 21 NH adults, and 174 conventional CI recipients on closed-set recognition of eight musical instruments playing a seven-note phrase. The Hybrid group all used a 10-mm internal electrode and CIS processing strategy while the CI group had long electrode arrays and they used different kinds of sound processing (Analog, MPEAK, SPEAK, ACE, CIS, SAS, and HiRes) The instruments were divided into three ranges of low-, mid- and high frequency instruments based on their fundamental frequencies. The aim of the study was to answer the question of how effective the hybrid CI was in the perception of real-world musical sounds and the recognition of musical instruments. The results showed that the performance of the conventional CI was clearly below that of the NH and hybrid groups. Similarly, the hybrid CI recipients performed more accurately than did the conventional CI users on real-world songs especially when the lyrics were removed. Another interesting finding was that the hybrid group showed more accurate recognition of instruments with low fundamental frequency, emphasizing the importance of the preservation of low frequency hearing for timbre and real–world song recognition.

In a study designed to assess the most important frequency range for melody recognition an experiment was conducted on five bimodal users (Kong, Cruz et al. 2004). The stimuli consisting of twelve notes that were played in three frequency ranges (low, mid and high) which were presented in three conditions: HA alone, CI alone and bimodal. The titles of the twelve melodies were displayed on a computer screen and the participant was asked to choose the melody that was presented. The three melody and three listening conditions were presented in random order. The average melody recognition performance across all participants and conditions was 45% when the participants used the HA alone which was 17% better than the CI alone condition. The result for the bimodal condition was similar to the HA alone condition. Another interesting point was large inter-subject variability in all of the conditions. Scores ranged from 19 to 90% for the HA alone; 18 to 80% for the CI alone and from 21 to 92% for the bimodal condition.

Pitch perception in electric-acoustic hearing

Although the above-mentioned studies indicated improvement in the perception of music with bilateral or bimodal configurations, this improvement was not enough for the CI users to listen to music as part of their daily listening habits. As the above studies showed even with such improvement, bilateral or bimodal CI users still showed a wide range of performance in the musical ability experiments for unknown reasons. Finding the source of this wide variability could be informative in creating new ways to improve music perception and appreciation.

In addition, there is some suspicion that the fundamental elements in music perception (such as pitch, melody and timbre perception) are not perceived evenly through CI and HA in bimodal hearing (Blamey, Dooley et al. 1996, Blamey, Dooley et al. 2000, Tyler, Parkinson et al. 2002, Kong, Stickney et al. 2005). Since satisfactory perception of music is determined in part by the perception of the above-mentioned elements, different perceptions in the two ears may hinder satisfactory music perception. It could be a reason why using a HA in the non-implanted ear cannot solve the problem of unsatisfactory music perception per se.

One reasonable assumption is that the perception of pitch in electric hearing is different from acoustic hearing. Although change in electrode position is represented as a change in place pitch (McDermott and Sucher 2006, Vermeire and Van de Heyning 2009), some bimodal CI users have reported different qualities of sounds in the implanted and non-implanted ears which indicates the confounding effect of the other aspects of sound on the perception of pitch (Vermeire and Van de Heyning 2009). To investigate the quality of sound in the implanted ear, Eddington, Dobelle et al. (1978) tested pitch matching with a pure tone in one CI user with normal hearing up to 1000 Hz in the non-implanted ear. They reported that pitch matching was difficult and suggested that the quality of sound in the implanted ear might be revealed with variations in the spectral characteristics of complex acoustic stimuli presented to the non-implanted ear. This suggestion was tested in one study with five bimodal CI users by Lazard, Marozeau et al. (2012). They asked their participants to match different types of sounds in the non-implanted ear to a pulse train presented to the most apical electrode in the implanted ear. They used filtered white noise, harmonic complex sounds and inharmonic complex sounds (in which the interval of each two harmonics was less than or more than F0). They reported that the perceived pitch was similar in terms of quality to inharmonic complex sound in 3 participants. Pitch perception has been investigated in experiments in which other aspects of sound have been changed. These aspects were intensity (Shannon 1983, Townshend, Cotter et al. 1987, Pijl 1997, Umat, McDermott et al. 2006, Arnoldner, Riss et al. 2008, Carlyon, Lynch et al. 2010, Green, Faulkner et al. 2012) and timbre or quality of sounds (Galvin, Fu et al. 2008, Ping, Yuan et al. 2012). Since the perceived quality or timbre of sound mediated by electric hearing may not be similar to that of acoustic hearing, this possibility has also been investigated (Carlyon, Macherey et al. 2010b).

The effect of loudness on the pitch perception of CI users

Loudness is the psychophysical attribute of the intensity of a sound and can vary from soft to loud. While intensity of a sound is measured in dBs, the loudness is measured in phons.

Loudness of a sound is determined in comparison with the loudness of a 1000 Hz sound with intensity of 40 dB. Each 10 dB increase in the intensity of a sound makes the loudness of a sound double. Uncontrolled variations in perceived pitch with changing intensity have been reported even in the pitch perception of normally hearing listeners (Thompson, Peter et al. 2012) especially for sounds with distinct changes in amplitude (Mcbeath and Neuhoff 2002). Essentially, variations in pitch with intensity may influence the enjoyment of music more than speech perception because musical sounds have wider dynamic ranges and more changes in amplitude and fundamental frequencies than speech sounds do. Similarly the perception of prosody, the comprehension of speech in tonal languages, and the perceptual segregation of competing sounds which depend on pitch perception may be influenced. The change in pitch perception with intensity is negligible in normally hearing listeners but studies on the effect of loudness in CI users suggest otherwise. Carlyon et al. (2010) tested the perception of pitch in 9 CI users and mentioned that the variability in pitch perception with loudness has been underestimated in CI users in contrast to normal hearing listeners whose pitch perception does not change much with loudness. This variability was reported to have a substantial effect on pitch judgments in CI users (2.3 semitones or 16% of the rate pitch). This is applicable when stimuli have wide dynamic ranges in general and when they present at a high level of intensity in particular. If the change in pitch perception with increasing level is substantial, it may give rise to a mismatch between the perceived pitch in acoustic and electric stimulation. This mismatch may have the potential to impede a significant improvement in music perception while using a HA in the opposite ear. Because of this possibility, the pitch-level interaction is worth studying in more detail.

Shannon (1983) reported that, in a pitch scaling experiment on a CI user, pitch increased with increasing level for a 1000-pps pulse train in a single subject at four levels of intensity on three electrodes in low, middle and high frequency ranges. He observed that pitch shifts resulting from amplitude variation could exceed those resulting from large variations in electrode position. He noted that the perception of pitch was completely different in electric hearing from acoustic hearing.

Townshend et al. (1987) used multiple electrodes in three CI users and two rates of stimulation of 100 and 200 pps. These rates were tested in different electrodes, one electrode at a time. The three participants performed a pitch ranking task for the stimuli varying in rate and current level. The results showed that there was a significant decrease in perceived pitch with increasing stimulation level. The variation of pitch with level was less pronounced for the 200 pps stimuli than for the 100 pps and was participant-dependent. They summarized the effect of level on pitch as present, but not pronounced.

In a study of three subjects, Pijl (1997) also concluded that pitch would significantly decrease with increasing level of the sound. The author studied pitch perception in CI users using two apical electrodes and six random pulse rates ranging from 82 to 464 pps in a pitch matching task. The stimulus levels were randomized between 90, 80, 70 and 60% of the electrical dynamic range. The task was to match and adjust the pulse rate of a comparison stimulus with a fixed reference stimulus while the two stimuli differed in loudness. The comparison and reference stimuli were presented either to a same electrode or two different electrodes. The level-dependent pitch changes were more significant for larger pulse rate and amplitude disparities between the reference and comparison stimuli, although no pulse rate matches were entirely satisfactory. Pijl concluded that it is difficult or impossible for electrically stimulated subjects to compensate for level-dependent pitch shifts with changes in pulse rate. In other words, the study showed that the CI users were able to produce highly replicable and accurate pulse rate matches only when the target and variable pulse rates had equal loudness and were presented to the same electrode.

It was initially imagined that the change in pitch with increasing level was associated with mode of stimulation in the CIs, but Arnolder et al. (2008) showed this change was not dependent on the mode of stimulation. They studied the relationship between intensity and pitch in sixteen post-lingually deafened patients with an average implant use of three years. One aim of this study was to find the effect of different modes of stimulation (monopolar versus bipolar) and different electrode types (perimodiolar versus lateral) on the relationship between pitch and intensity. They used a reference tone with fixed comfortable loudness level and a second tone with the same acoustic features as the first one with the exception of variation in intensity. The participants' task was to estimate the perceived pitch of the second tone on a scale from 0 (the lowest pitch) to 100 (the highest pitch). They noticed that the direction of the level effect on pitch judgment was not changed by the mode of stimulation in CI users and that the locations of electrodes had a marginally statistically significant effect. Using monopolar stimulation, for fourteen people who perceived a clear pitch, ten perceived lower pitch with the increase in intensity and the remaining four showed the opposite trend. Nine people out of twelve CI users who had a clear pitch perception reported a decrease in pitch and three perceived an increased pitch with increased intensity in bipolar stimulation.

While three studies (Shannon 1983, Townshend, Cotter et al. 1987, Pijl 1997) attributed the change in pitch with level to a cognitive stage of processing such as a change in the bias by which participants ordered their perception of pitch, Carlyon et al. (2010) showed that this effect varied between electrodes and/or rates for a given subject. They examined rate discrimination of nine postlingually deafened CI users with both monopolar and bipolar modes and concluded that small variations in level had a genuine effect on the perception of pitch. The participants had to adjust the level of a 200-pps stimulus with reference to a 100-pps stimulus which was presented to the same electrode. One interesting point of this study is that they found a real effect of the increase in the level on pitch that could overcome the difference in pulse rate. These effects were idiosyncratic across subjects, electrodes, and standard pulse rates, but were stable over time, and for changes from bipolar to monopolar stimulation. In addition, they advised against roving of loudness in studies of pitch perception, as they noted the effect of level on pitch judgment is robust, despite its idiosyncratic nature. The roving of loudness could potentially disrupt the way in which the effect of loudness shows itself.

The effect of loudness on the perception of pitch has been investigated on people with residual hearing in the non-implanted ears as well. In one study of nine CI users with residual hearing in the non-implanted ears, frequency selectivity of the non-implanted ears and pitch matching between acoustic and electric hearing were tested (Green, Faulkner et al. 2012). The results of a frequency selectivity experiment showed a large variance among the people tested. Even participants with similar audiograms showed very different patterns of frequency selectivity. In a pitch matching test, an adjustment method was used to match the pitch precepts elicited by pulse trains on individual electrodes with acoustic pure tones, narrow-band noises and band-pass filtered pulse trains. The test was performed at different levels of intensity and on different electrodes (frequency). A wide variation of the effect of level at both low and high frequencies was observed. This effect of intensity varied from one person to another. Even in participants with similar audiograms and with reliable frequency selectivity, the effect of intensity on perceived pitch was not similar, and the direction of change was not similar for different electrodes either. Another finding was that the perceived pitch changed differently for low and high frequency within participants. They also found higher pitch matches for band-pass filtered pulse trains than sinusoidal sounds and bands of noise, but this pattern was not consistent across electrodes. They recommended that frequency selectivity was not a sufficient condition for reliable pitch matching. There were two participants with reliable pitch matches. For one of them, perceived pitch increased with increase in intensity while the reverse pattern was found for another participant. For most cases in the study, the pitch matches varied from the nominal centre frequency of the bandwidth of the electrode for the most apical electrode.

The above-mentioned variability of pitch and loudness has been attributed to several peripheral factors. One of these factors is the electrode-neuron interface. The electrode-neuron interface describes the position of electrodes inside the cochlea, and the distance between each electrode and its targeted spiral ganglions. The other factor is the distribution and survival of the ganglion cells within the modiolus as a consequence of hearing pathology.

The electrode-neuron interface

In NH listeners, the tight connection of the dendrites of the auditory neurons to the hair cells in the cochlea results in highly tonotopic organization in the coding of frequency. The dendrites of the auditory neurons are connected to the hair cells which best respond to high frequency at the base of cochlea and low frequency at the apex in a place-specific manner along the frequency gradient of the cochlea. The somas of these neurons are located in Rosenthal's canal within the modiolus and they form spiral ganglions. The spiral ganglions in human are clustered with direct physical contacts with each other. In contrast, sensorineural hearing loss causes the degeneration of hair cells and the neural elements attached to them. The loss of hair cells can reduce the population of spiral ganglions but they survive to some degree even after longstanding deafness (Nadol, Young et al. 1989, Fayad, Linthicum et al. 1991, Zilberstein, Liberman et al. 2012). Therefore, the cochlear implant can bypass the hair cells and stimulate the spiral ganglions located within the modiolus.

The electrode array of a cochlear implant is inserted into the scala tympani, which is filled with perilymph fluid. Electrical stimulation is accomplished by delivering electrical currents from the electrodes to the auditory neurons. When an electrical current is delivered from an intracochlear electrode, an electrical field is generated and spiral ganglions are stimulated. Since there is some distance between the electrode contacts and the spiral ganglions, and the perilymph is an excellent conducting solution, the electrical field stimulates a wide region of spiral ganglions. The ideal position for electrodes is close to the ganglions so they can stimulate their target population of neurons and different electrodes can transmit spectral and place cue information optimally. In addition to the lateral position of the electrodes in the scala tympani, the insertion depth and angle of the electrode array may be different in different people. Even with similar electrode insertion depths, the positions of the electrodes inside the cochlea may be different (Kós, Boëx et al. 2005). This is why manufacturers try to make electrode arrays which can lie in very close proximity to the modiolus to avoid current spreading. In fact, low spectral resolution in the stimulation of the auditory neurons due to current spreading is one of the major problems of CIs in providing reliable pitch perception.

The nerve bundles from the hair cells in the basal coil of a normal cochlea take a relatively direct radial course into the modiolus, but in the middle and apical turns, the path of the fibres varies significantly because Rosenthal's canal is much shorter than the basilar membrane and does not extend to the apical turn. Therefore, the spiral ganglions of the middle and apical turns of the cochlea are not adjacent to their corresponding hair cells.

This causes the auditory neurons in these areas to be densely packed (Bredberg, Engstrom et al. 1965, Glueckert, Pfaller et al. 2005). Therefore with spreading of current, a range of auditory neurons are stimulated. This is believed to be one of the reasons for low spectral resolution and poor pitch perception observed in CI users. Current spreading is more likely to take place for loud sounds that produce larger electric currents (Honert and Stypulkowski 1987, Bierer 2010) and when the electrodes are not positioned close to the modiolus (Briaire and Frijns 2000, Hughes and Abbas 2006). In fact, a poor electrode-neuron interface which may cause wider current spreading has been put forward as a justification for the changes in the perceived pitch of loud sounds in CI users. One of the findings of the above mentioned studies of the effect of loudness on the perception of pitch was the variability of that effect for different electrodes within the same cochlea (Green, Faulkner et al. 2012). This may be explained by different positions of different electrodes relative to the spiral ganglions. In a perimodiolar electrode array, some electrodes may be close to the modiolus and spiral ganglions, giving a more localized current field and better spectral resolution. In this case, loudness and current spread are less likely to affect spectral selectivity than if the electrode lies further from the modiolus (i.e. close to the lateral wall of the cochlea). It has been suggested that for a poor electrode-neuron interface, the thresholds are higher and more electrical current is needed for stimuli to reach threshold (Bierer 2010). It is worth mentioning that fibrosis tissue and bony structures are formed in some CI users after implantation. These structures have high impedance and change the pathway of the electrical current within cochlea. This can increase the effective electrode-neuron distance and make spatial resolution and pitch perception poorer for some electrodes (Bierer 2010).

The survival of the spiral ganglion cells

Different hearing pathologies can induce some degree of loss in the population of the spiral ganglions. The amount of spiral ganglion loss depends on several factors including the etiology and duration of hearing loss and varies in the apex and base of the cochlea. (Nadol, Young et al. 1989, Nadol 1997). The above-mentioned factors may cause degeneration of the spiral ganglion in a way which cannot be predicted from behavioural measurements. There is no direct way to assess the spiral ganglion cell population and no strong evidence that neural survival has a significant effect on CI performance on speech perception tasks (Blamey 1997). It has been suggested that degeneration in the population of the spiral ganglion cells does not shown itself in monopolar mode of stimulation (Goldwyn, Bierer et al. 2010). When current spreading occurs, depending on the degree of the degeneration of the spiral ganglions surrounding the stimulated electrode, the perception of pitch may vary. It has been suggested that wider current spread may produce a "buzzy" percept and narrower current spread may produce a purer pitch-like percept (Pauka 1989). For example, if the spiral ganglions of the stimulated electrode are intact and the electrode lies close to its targeted neurons, the perception of pitch may not change very much for loud sounds and the perception of pitch may be less noisy. On the other hand, when the target neurons are degenerated, at loud levels the perception and quality of pitch may be determined by the neighbouring intact spiral ganglions. Therefore the perceived pitch may be quite different in comparison with a cochlea in which the target neurons are intact.

Electrode-acoustic frequency-place mismatch

Several studies have tried to compare frequency tonotopy of the implanted and non-implanted ears at low frequencies in CI people with residual hearing in the non-implanted ear (Eddington, Dobelle et al. 1978, Blamey, Dooley et al. 1996, Baumann and Nobbe 2006, Boëx, Baud et al. 2006, Dorman, Spahr et al. 2007, Baumann, Rader et al. 2011). Although Eddington et al. 1978 reported that the acoustic-electric pitch matches were similar to those expected from Greenwood's function, others noticed that the acoustic matches to electrical stimulation were lower than predicted by Greenwood's function (Eddington, Dobelle et al. 1978, Blamey, Dooley et al. 1996, Baumann and Nobbe 2006, Boëx, Baud et al. 2006, Dorman, Spahr et al. 2007, Baumann, Rader et al. 2011). It is known that the length of the cochlea varies from person to person from 32 to 35 millimetres. In addition to this variability, the insertion depth of the electrode array of a cochlear implant can influence the place of stimulation. Different combinations of the cochlea length and insertion depth are possible. These combinations could vary from a short cochlea (e.g. 32 mm) which has been implanted with a deep electrode array insertion (e.g. 25 mm) to a 35 mm cochlea with short insertion of the electrode array (e.g. 20 mm).

Figure 1-4 shows the range of possible stimulation places between the two aforementioned extreme examples. The CF predicted by the Greenwood function for these extremes differs by up to 20 MIDI notes or almost two octaves (see Figure 1-4).

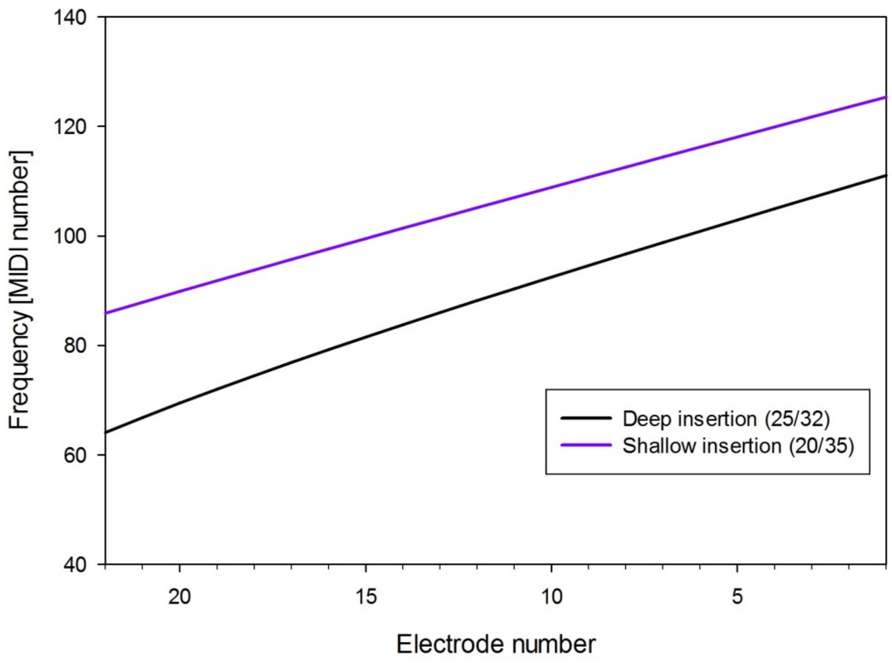

Figure 1-4: the estimated CFs for electrodes of CIs with different insertion depth and length of cochlea

This implies that there may be a frequency-place mismatch between electric and acoustic stimulation due to the limited insertion depth or length of the electrode array. Some researchers report that this mismatch may be reduced over time by perceptual adaptation (Svirsky, Silveira et al. 2004, Reiss, Turner et al. 2007, McDermott, Sucher et al. 2009) but others have not observed such adaptation (Carlyon, Macherey et al. 2010b, Baumann, Rader et al. 2011). It seems that such adaptation does not happen to all CI users. If a mismatch remains over time, it does not allow bimodal CI users to have a unified pitch perception which may be necessary for good music perception with two devices. Besides this fact and even in the case of adaptation, loudness could influence the perception of pitch differently in electric and acoustic hearing.

Dead regions in non-implanted ears

Places where there are no functioning IHCs and/or neurons are referred as "dead regions"(Moore 2004). The perception of pitch in non-implanted ears may be affected by the presence of dead regions. A tone with a frequency falling in a dead region can be detected, if it has enough intensity, through its spread of excitation towards the apical or basal places where there are functioning IHCs and neurons (Moore and Alcántara 2001, Moore 2004). This kind of sound detection is called off-frequency listening. It is not possible to determine dead regions based on the audiogram, but they are likely to be present at a given frequency when the hearing loss at that frequency is 70 dB or more (Moore, Glasberg et al. 2010). In electric-acoustic pitch matching, the presence of dead regions can change the frequency selected as a match to the electrically elicited pitch. Therefore, off-frequency listening may help to explain the discrepancy between the pitch perception of electric and acoustic hearing.

The starting point and rationale for this research

The above review suggests that pitch judgments might not be independent of changes in intensity (or its psychological correlate loudness) in CI users and that this effect is worth studying in more detail with more subjects using different frequencies and electrodes. Another factor which may influence pitch perception of CI users is the timbre or quality of sounds (Shannon 1983, Ping, Yuan et al. 2012). Although most studies have been done on CI users, pitch judgments for bimodal stimulation could be more complicated because subjects are listening to sounds through two different devices with two different modes of hearing (i.e. acoustic and electric). Interestingly, bimodal stimulation provides an opportunity for us to do experiments on pitch perception through acoustic and electric hearing and to examine their relationship with changing level.

It is reported that pitch may depend on level when either the dynamic range of the stimulus is wide or a stimulus is presented at a high intensity level. Taking the wide dynamic range of musical pieces into account, it seems plausible that the pitch perception of musical sounds may be affected by intensity in everyday situations. It may be possible to design a new sound processing strategy tailored to music perception by compensating for the dependence of pitch perception on level and loudness, or the current CI technology may be modified to account for possible changes in pitch with levels of intensity in individual listeners.

Hypothesis

The following hypothesis is the focus of chapters three to six: "the perceived pitch of sounds presented to a CI depends on the intensity and quality of the sound". This hypothesis is based on the above literature review which throws doubt on the independence of the perception of pitch from the perception of loudness. The possible mechanisms by which loudness might influence the perception of pitch for each stimulus will be introduced and discussed fully in chapter 2. To conduct a thorough investigation of the possible effects of intensity on the perception of pitch, three stimulus types which were representative of the wide range of sounds used in CI pitch perception and music research were selected: a pulse train which was confined to a single electrode, a pure tone and a piano note. Since the literature pointed out the possibility that the quality of sound may affect the perception of pitch, all three CI stimuli were tested against two different acoustic sound qualities in the non-implanted ear.

Chapter 2: Pitch matching

Introduction

As mentioned in chapter 1, one way of improving music perception in CI users is bimodal hearing or combination of electric and acoustic hearing. As the perception of the fundamental frequency (F0) with acoustic hearing is better in comparison with electric hearing alone, it is believed that this configuration can improve pitch perception which in turn may lead to better music perception. However, using a HA in the non-implanted ear along with a CI in the implanted ear may not yield satisfactory music perception. This suggests the necessity of some modifications in CIs or HAs or both devices to reach a balanced and supportive cooperation between the two modalities of hearing. The review in chapter 1 raises some questions which will be addressed here: Is the perception of pitch of a sound similar with acoustic and electric hearing? Does the perception of pitch depend on the intensity of sounds? Does the perception of pitch depend on the quality of sounds presented to the two ears?

As the literature review in chapter 1 showed, some recent studies have suggested other aspects of sound, in addition to frequency, could play a role in the perception of pitch in electric hearing. One of these factors is the intensity of sounds presented to the sound processors of CIs. Most of the published data for normally hearing listeners who hear acoustically have shown that intensity does not change the perception of pitch noticeably (Verschuure and Meeteren 1975). However, there were large individual differences both in the size and direction of the shifts of pitch perception (Terhardt 1974b). If pitch perception is affected by intensity in electric hearing (Townshend, Cotter et al. 1987, Pijl 1997, Arnoldner, Riss et al. 2008, Carlyon, Lynch et al. 2010) but not in acoustic hearing, the perception of pitch in bimodal hearing would be distorted. Even if intensity can change the perception of pitch in both modalities but the direction of these changes are not similar, a similar pitch would not be perceived from a single sound in two modalities of hearing. The hypothesis of this thesis is as follows: the perceived pitch of sounds presented to a CI will depend on the intensity and quality of the sound.

Therefore, this thesis will study the perception of pitch with differences in intensity and quality of sound. Beforehand, it is worthwhile to look into how sound is coded by CIs.

Sound Processing in ACE Systems

The ACE strategy has 22 overlapping band-pass filters for analysing the sound. Each filter is linked with its corresponding electrode inside the cochlea. The signal is processed by the band-pass filters. The ACE strategy, used in the Nucleus implant, is based on a so-called N of M principle which means that N out of 22 (M) available electrodes are chosen for stimulation. After the signal has passed through these 22 band-pass filters, the envelope information for every frequency band is extracted, and then N frequency bands with the largest amplitudes will be picked and sent to the corresponding electrodes for stimulation. Typically the original spectrum is reproduced by up to 10 variable channels (McDermott 2004), although it should be noted that the participants in this study had numbers of channels ranging from 2 to 12. The processing is shown in Figure 2-1.

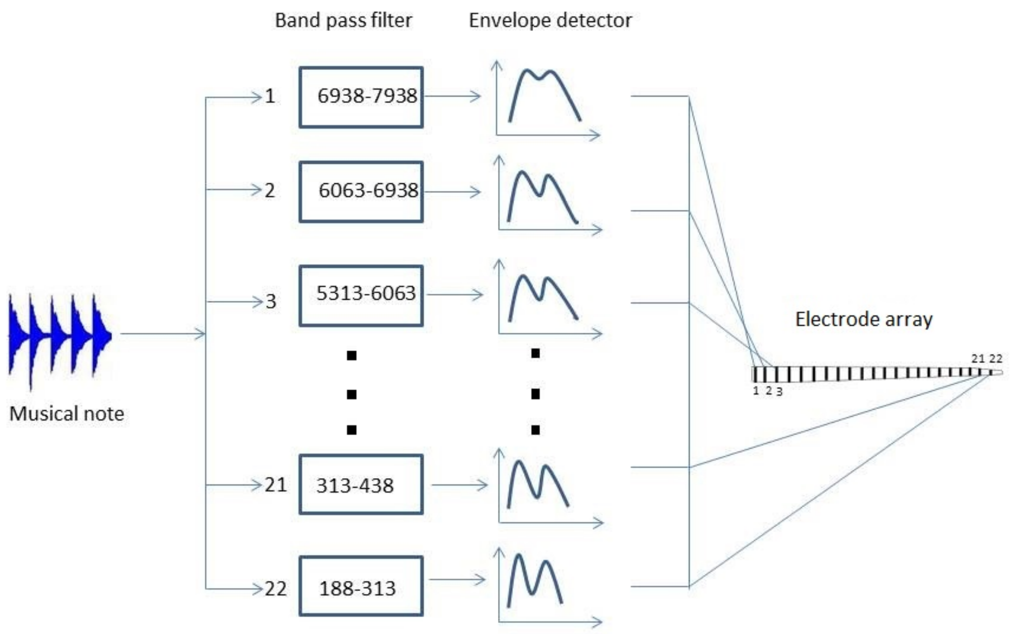

Figure 2-1: a functional block diagram of the ACE sound processor

The musical sound in this figure has been broken down into its components by passing though the filter bank. After that, the envelope of each filtered signal is determined and the outputs of some of the filters (N-of-M) with higher intensity are sent to their corresponding electrodes to stimulate the auditory neurons.

Acoustic sounds in the environment have a wide range of intensity. However, sound processors select a range of acoustic input to map into the recipient's electrical dynamic range. In the current cochlear implant, the lowest acoustic intensity which can induce electrical stimulation has the intensity of 20 to 30 dB SPL (Wolfe and Schafer 2010). This limit is called T-SPL. If an acoustic sound is below T-SPL, it does not stimulate the electrodes inside the cochlea. The acoustic energy that corresponds to the maximum stimulation of the electrodes is called C-SPL. If an acoustic sound is above C-SPL, the corresponding electrodes will be stimulated at its maximum allowable current (C level).

The frequency bands which have energy less than T-SPL do not stimulate their corresponding electrodes at all. The frequency bands with energy above C-SPL are subject to infinite compression. This means they are attenuated and suppressed so that they do not produce too loud a sound.

How can intensity change pitch perception in cochlear implant users?

When a sound is presented to the sound processor of a cochlear implant, a set number of band-pass filters estimate the short-term spectrum of the input signal. The filters have frequency responses which cover a wide bandwidth from very low frequencies to high frequencies. The levels of the outputs of the filters are compared to each other, and only the outputs with the highest levels are selected and sent to the corresponding electrodes. The outputs with specified levels are converted to digital data and are transferred to the implanted receiver. The receiver decodes the signal and the selected signal levels are converted into appropriate current levels of electric stimulation which are delivered to the active electrodes. The resulting stimulation pattern comprises a series of pulses delivered at a constant rate to the electrodes. These pulses are biphasic and are presented in an interleaved form. They stimulate neural elements close to the stimulated electrodes.

When the intensity of a sound presented to an electrode increases, more neural elements are stimulated (Honert and Stypulkowski 1987, Bierer 2010). Therefore the neural populations which are responsible for coding sound at low and high intensities are different, and a different perception of pitch may occur. Figure 2-2 shows a schematic representation of the same sound at two different levels of intensity. This phenomenon is called "current spreading" in this thesis. All figures 2-3 to 2-8 are the outputs of an ACE sound processing strategy when a pure tone at different levels of intensity was input to the processor and figure 2-9 is the output of the sound processor for a piano note (Marozeau 2013).

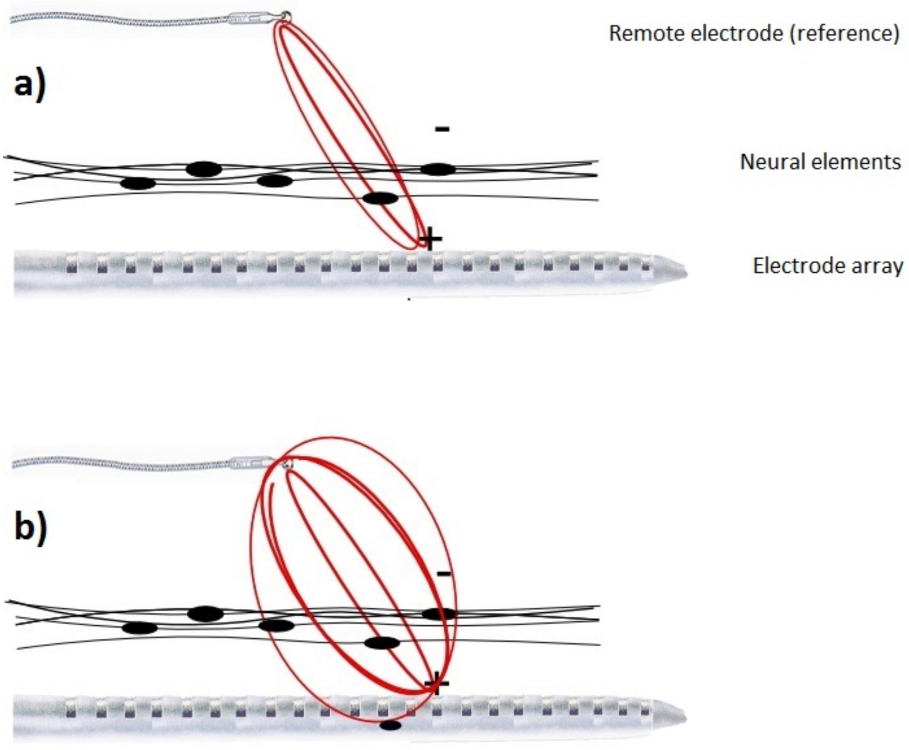

Figure 2-2: Current spreading by increase in intensity of sound

Schematic representation of the stimulated population of auditory neurons when a) the input is presented with low intensity and when b) the input sound has high intensity and current spreading occurs.

In figure 2-2 current is delivered to a single electrode on the electrode array. It spreads out as it passes through the neural elements to get to the remote return electrode. The extent of current spreading is not easily determined by modelling or experiment.

When a pure tone is presented to the sound processor with a low level of intensity, a band-pass filter whose bandwidth includes the frequency of the pure tone is the only filter which has enough amplitude at the envelope detection stage to produce electrical stimulation. Therefore the output of this filter will be picked and coded and sent to the corresponding electrode inside the cochlea (Clark 2003). This is shown in figure 2-3 which was produced by feeding a 590 Hz pure tone into a sound processor with an everyday map of a CI user. The horizontal axis shows the activation on different electrodes [electrode number 1 to 22] for a pure tone with 34 dB SPL. The vertical bar indicates the amount of activation on each electrode in milliamps. The only substantial and perceptible activation is on electrode number 19, since the frequency of the pure tone was close to the centre frequency of this electrode. Due to some internal noise there is some activation on the other electrodes but this activation is negligible compared to the activation on electrode 19.

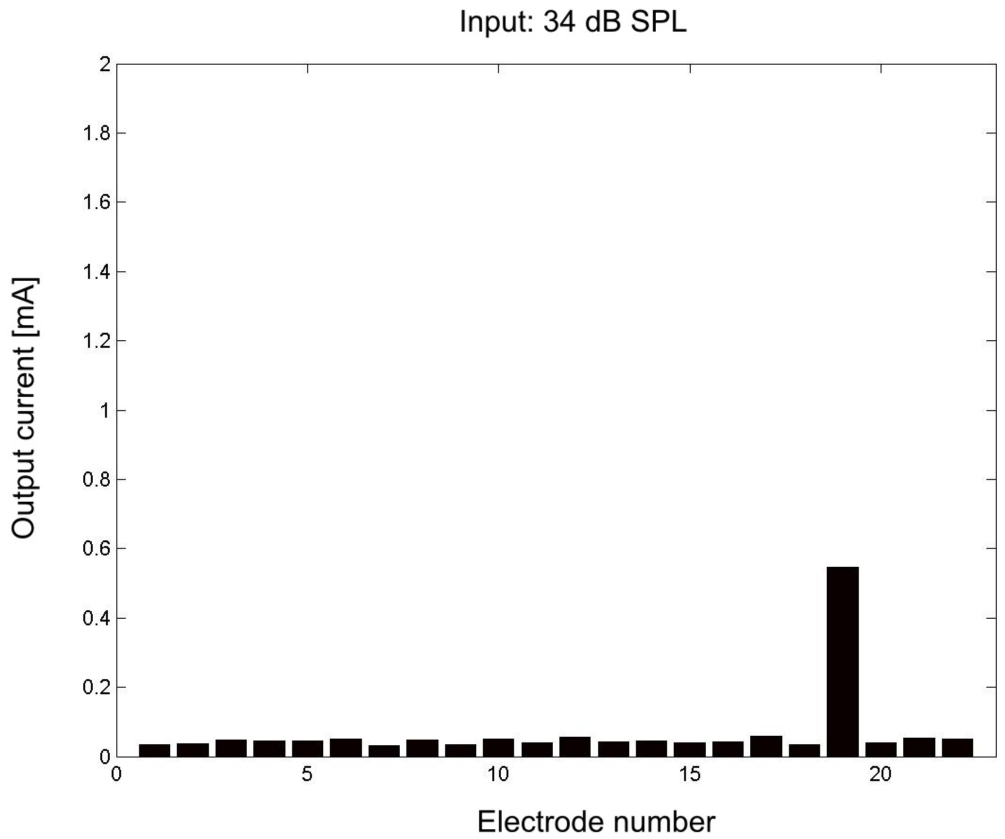

Figure 2-3: Electrode activation pattern for a pure tone at 34 dB SPL

At low intensity level of the input sounds, only one filter has enough intensity to stimulate its corresponding electrode and that is the filter which contains the frequency of the pure tone (electrode number 19). However, all other electrodes receive some negligible activation due to the presence of the sound processor's internal noise.

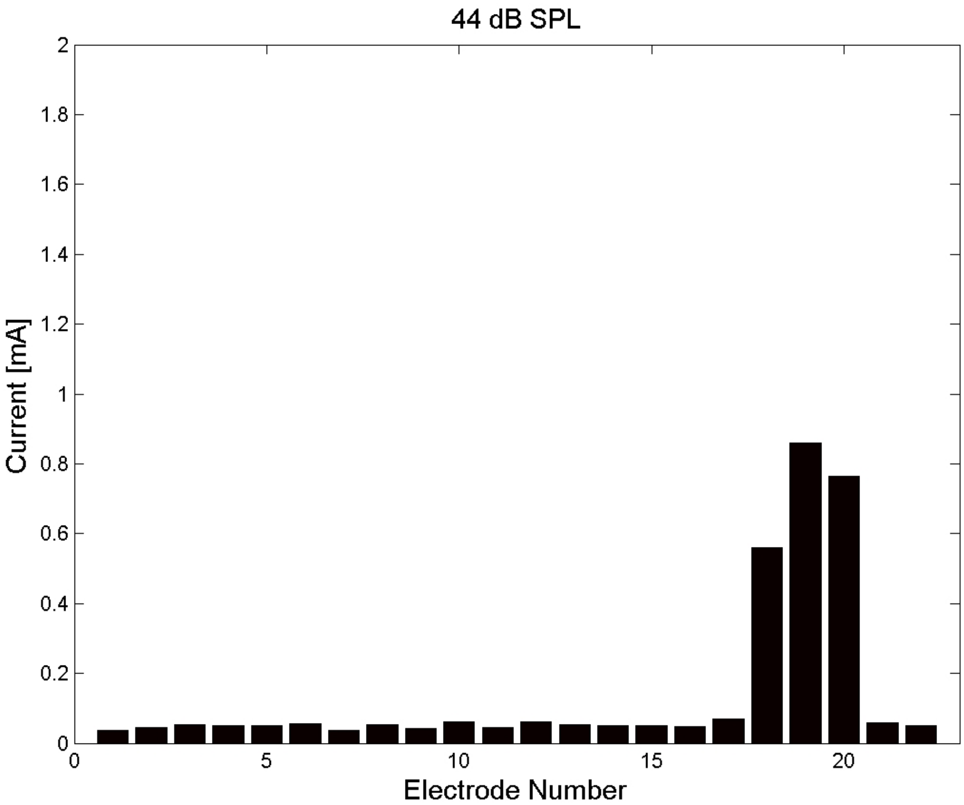

Figure 2-4: Electrode activation pattern for a pure tone at 44 dB SPL

By increasing the intensity of the input sound, more than one filter receives enough intensity to stimulate the electrodes inside the cochlea. At 44 dB SPL, in addition to electrode number 19, electrodes 18 and 20 receive stimulation from their corresponding filters.

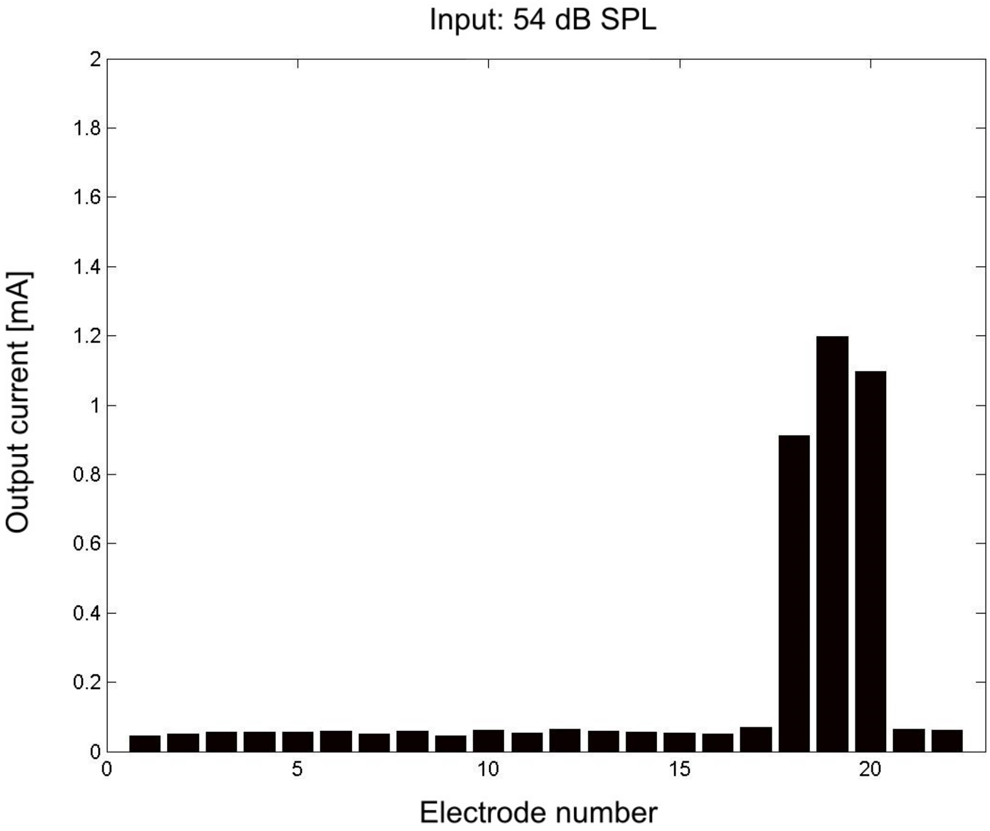

Figure 2-5: Electrode activation pattern for a pure tone at 54 dB SPL

The increase in the magnitude of stimulation caused by increased intensity is observed for electrodes 19, 18 and 20.

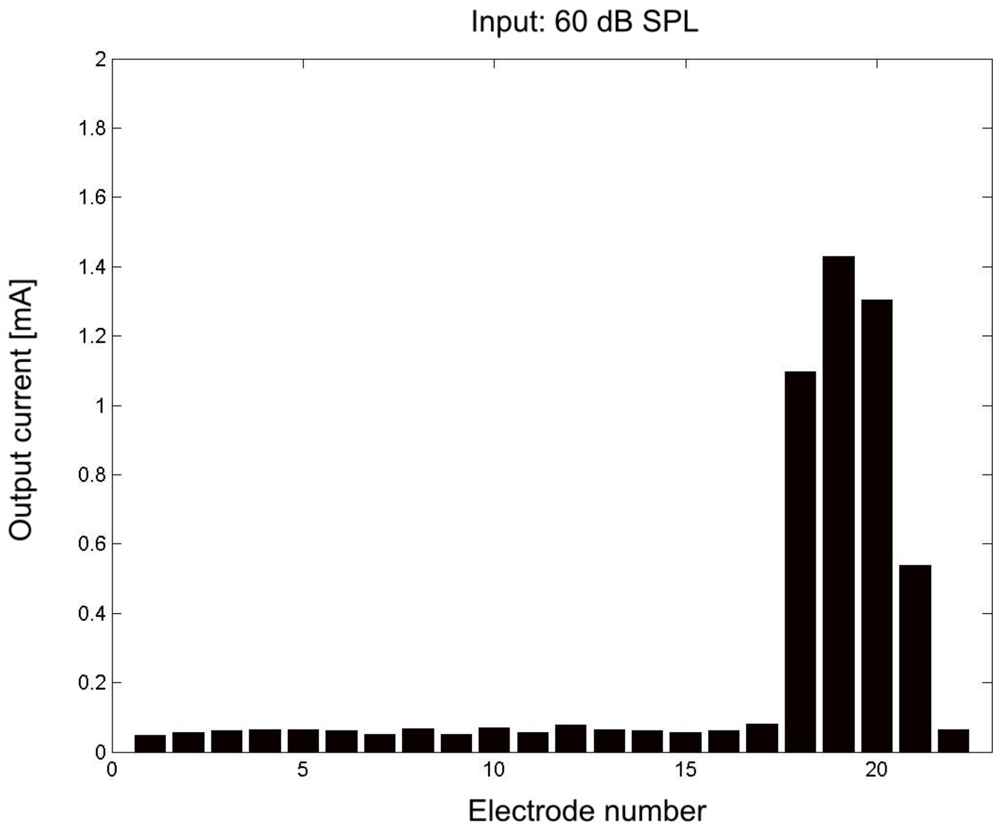

Figure 2-6: Electrode activation pattern for a pure tone at 60 dB SPL

When the intensity of the input sound increases further, stimulation spreads to a more distant electrode (electrode number 21).

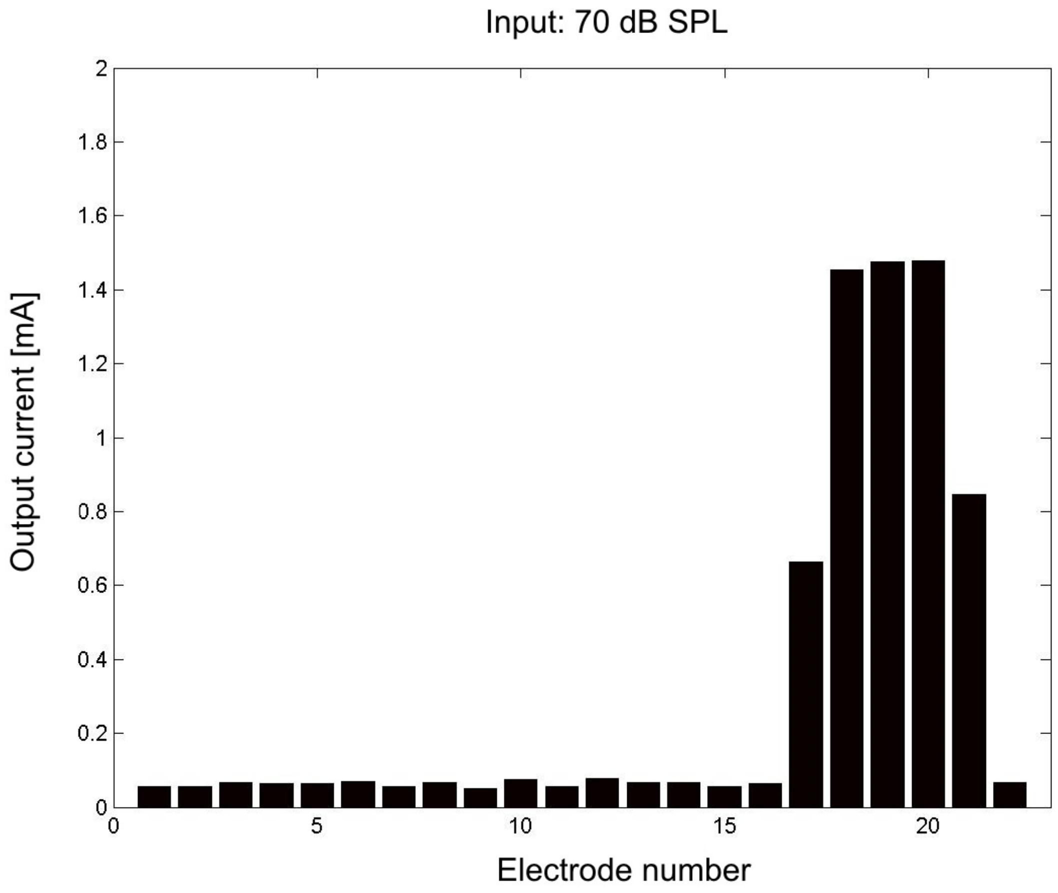

Figure 2-7: Electrode activation pattern for a pure tone at 70 dB SPL

When increase in intensity cannot induce more stimulation on an electrode, other electrodes absorb the intensity and receive stimulation. In this figure, electrode numbers 18, 19 and 20 have reached their maximum stimulation. Therefore increase in intensity results in more stimulation of electrodes 17 and 21.

As the intensity of the pure tone grows, due to the overlapping nature of the band-pass filters, the other neighbouring electrodes receive some activation which is above the activation induced by noise [figures 2-4 to 2-7]. Depending on the frequency of the pure tone and the position of the main electrode, the stimulated electrodes vary (Wilson and Dorman 2008). This kind of change in the pattern of electrode stimulation is called "electrode activation spreading" in this thesis. For the most apical electrode (electrode 22), the activation spreads towards the basal electrodes, since there are no electrodes on the apical side to receive the activation. For an electrode such as electrode number 19, the activation spreads on both the apical and basal sides. With an increase in intensity in addition to growth in the amplitude on the main electrode, the neighbouring electrodes also receive higher amplitudes. However, the main activation is maintained on electrode 19 until the time that the main electrode reaches C level (maximum comfortable level) and is saturated [figure 2-7]. The saturation level is a level after which the increase in intensity at a given electrode cannot induce greater electrical stimulation. When saturation occurs for the main electrode, most of the growth in activation is transferred to the electrodes adjacent to the main electrode. When these electrodes become saturated with the increase in intensity of the pure tone, more distant electrodes take up some activation [figure 3-8]. Figure 3-8 shows saturation for electrodes numbers 19, 18 and 20 and the spread of activation to other electrodes when the pure tone sound is presented at a level of 74 dB SPL. It is believed the presence of activation on more than one electrode can be a reason for change in the pitch of pure tones with different levels of intensity (Marozeau 2013).

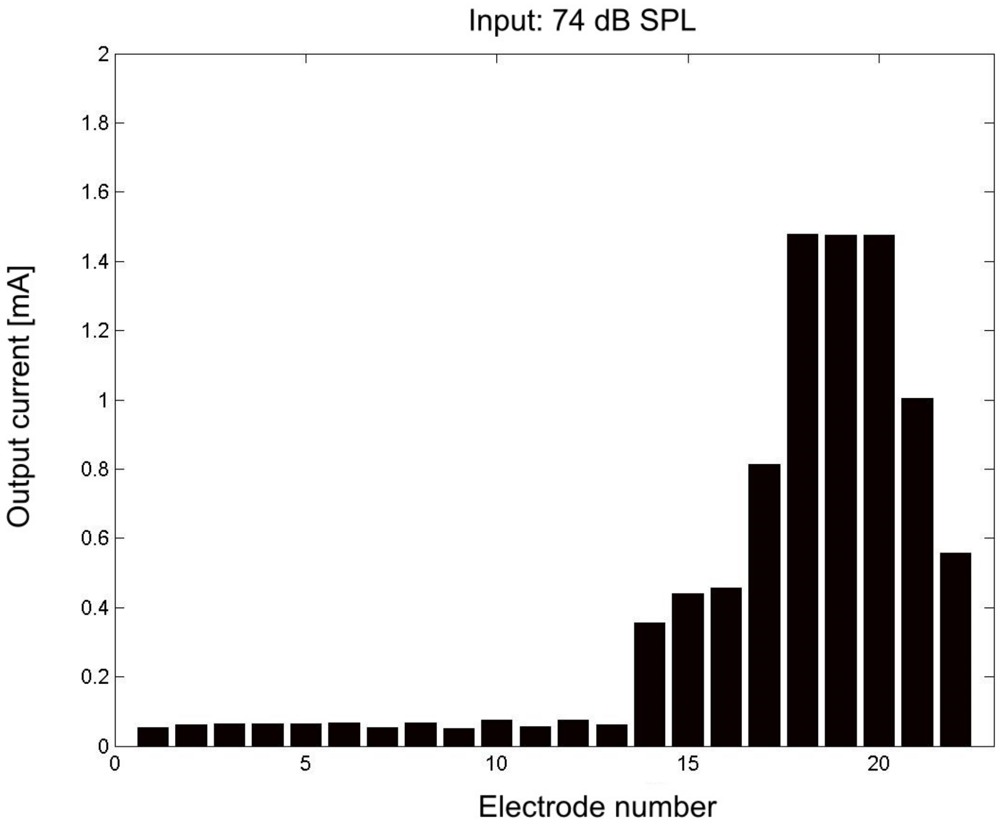

Figure 2-8: Electrode activation pattern at 74 dB SPL

At 74 dB SPL, in addition to saturation of stimulation for electrodes 18, 19 and 20 and more growth in the stimulation of electrodes 17 and 21, other more distant electrodes also receive stimulation (electrodes 14, 15, 16 and 22).

Figures 2-3 to 2-8 show the electrode activation spreading for a range of inputs from 30 dB to 74 dB. This kind of spreading is likely to be a major contributor to pitch changes in real-life situations.

When the input sound is a complex sound like a musical note, the pattern of spread of activation becomes more complicated. Musical notes are comprised of a fundamental frequency and some harmonics. When this type of sound is presented to a cochlear implant, the sound processor filter bank analyses the fundamental frequency and harmonics of the signal. The output of each filter will be sent to the corresponding electrode. Even at low levels of intensity, more than one electrode is activated by the sound because of the harmonics. When intensity is increased, the neighbouring electrodes of each component of the complex sound receive activation due to electrode activation spreading. There is spread in activation due to both electrode activation and current spreading, in addition to the presence of activation on many electrodes due to representation of harmonics ("spectral spreading"). Figure 2-9 shows the output of an ACE sound processor when a piano note with the F0 of 209 was input at different levels of intensity to the sound processor. Figure 2-9 shows the output of an ACE sound processor when a piano note with the F0 of 209 Hz was input at different levels of intensity to the sound processor. This figure was made of averaging a lot of frames of stimulation at different levels of intensity. In each frame, only 8 to 10 electrodes are normally chosen to receive electrical stimulations. However, since the figure shows the sum of many frames and the stimulated electrodes vary from one frame to another, more than 10 electrodes seem to receive stimulation in the averaged output which shows the overlapped stimulation pattern of many frames.

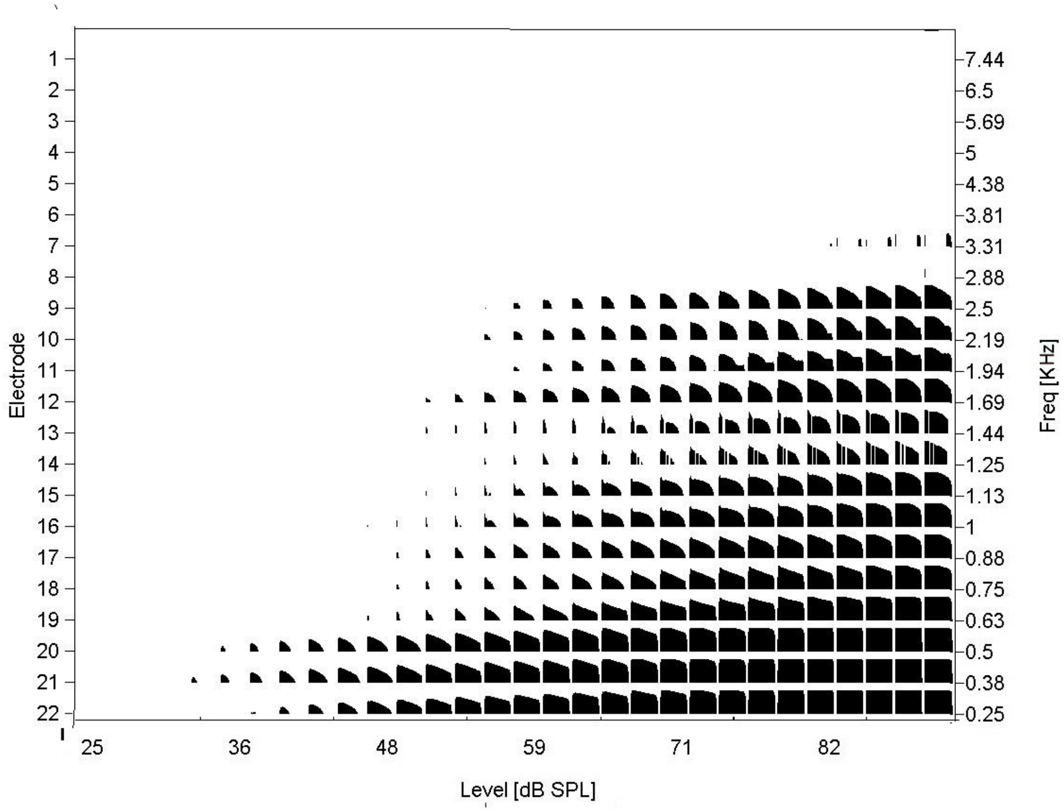

Figure 2-9: Electrical stimulation representing the harmonics of a piano note (209 Hz) at increasing levels of intensity

This figure shows the stimulation received by each electrode when a piano note was played from low level to high levels of intensity. The horizontal axis shows the intensity of each note. The left vertical axis shows the electrode numbers and the right vertical axis shows the centre frequencies of the electrodes (in KHz) from the electrode with lowest centre frequency (electrode number 22) to the electrode with the highest centre frequency (electrode number 1). The electrodes receiving stimulation are designated by dark bars. The height of the bar shows the intensity of the received stimulation. The fundamental frequency of the piano note was 209 Hz. The overtone harmonics of this piano note are 418, 627, 836, 1045, 1254, 1463, 1672, 1881, 2090 and 2299 Hz corresponding to electrodes. Since in this piano note, the first overtone harmonic (418) had higher amplitude than the fundamental frequency, electrode 21 was stimulated at a low level of intensity only. As intensity increased, the other harmonics of the piano note were represented and in addition, there was activation on other electrodes due to electrode activation spread.

Even in normal hearing listeners, the resolvability of harmonics has a significant role in pitch perception of complex sounds. While cochlear implant users have a limited ability in resolving the harmonics of a complex tone, both current and electrode activation spreading can impair this limited ability even more. The effect of the spread of electrode activation could be especially detrimental since the pattern of spread in activation varies by the electrode position. For example, the spread of activation for the fundamental frequency would be in the basal direction, while for higher harmonics, the activation spreads on both basal and apical sides.

The three kinds of spread described above (current spreading, electrode activation spreading, and spectral spreading) show the effect of intensity on the representation of sound in cochlear implant coding. The following experiments have been designed to address the hypothesis: the perceived pitch of sounds presented to a CI will depend on the intensity and quality of the sound using single electrodes, pure tones, and harmonic complexes.

Main hypothesis

The intensity and quality of sound can affect the pitch of sounds perceived by cochlear implant users. To test this hypothesis, pitch perception was assessed for different combinations of intensity and quality of sounds. The task was pitch matching between two modalities of electric and acoustic hearing.

Three possible mechanisms were recognised by which intensity could affect the perception of pitch. They were current spreading, electrode activation spreading and spectral spreading. They were studied at soft and loud levels of intensity and low and high frequencies in three experiments. To assess each mechanism, a specific stimulus type was required: 1) for the first mechanism, all stimulation was kept on just one electrode (therefore, this is called the single electrode experiment). The stimulus type that suited this experiment was an electrical pulse train which was confined to one electrode at both soft and loud levels of intensity. 2) For the second mechanism, a pure tone was the stimulus type, also presented at soft and loud levels. Although a pure tone with a given frequency stimulates one corresponding electrode at soft levels, other neighbouring electrodes receive stimulation as intensity increases. This leakage of activation to the neighbouring electrodes occurs along with current spread to the neighbouring neurons for each electrode and is called electrode activation spread. 3) For the third mechanism, the perception of pitch of a piano note was studied to represent the effect of intensity on pitch elicited by musical sounds. As a harmonic complex sound has fundamental frequency and harmonics, regardless of the intensity of the sound, several electrodes receive stimulation such that each electrode corresponds to one component of the complex sound if the difference between harmonics is wide enough to stimulate different electrodes. In addition, at loud levels, leakage of activation to neighbouring electrodes is probable. This leakage of activation happens along with current spread to the neighbouring neurons for each electrode. This kind of spread is called spectral spread. For each experiment, specific hypotheses are described.

The assessment of the above-mentioned mechanisms required employing different sound qualities. Since the perception of pitch of each sound type was assessed in a bimodal pitch matching task, the quality of sound in the non-implanted ear could be influential as well. Since the pitch of a pure tone is derived from its frequency, changes in the perception of pitches of different sound types presented to the implanted ear were monitored in the perceived pitches of pure tones in the non-implanted ear. As already mentioned, Lazard et al. (2012) found that the sensation of a pulse train in the implanted ear was more similar to a complex sound in the non-implanted ear rather than to a pure tone or noise. Therefore, the three above-mentioned experiments were repeated firstly using a pure tone and secondly with a complex tone being presented to the non-implanted ear. Table 2-1 shows the type of reference and adjustable sounds for all six experiments.

Experiment	Reference sound	Adjustable sound
A-1	Single electrode pulse train	Pure tone
A-2	Single electrode pulse train	Complex tone
B-1	Pure tone	Pure tone
B-2	Pure tone	Complex tone
C-1	Piano note	Pure tone
C-2	Piano note	Complex tone

Table 2-1: The type of reference and adjustable sounds in each experiment

It was hypothesised that similarity of sound types in the ears with different modalities would facilitate the perception of pitch and possible effects of change in intensity. The degree of similarity was rated after each matching trial based on all sound qualities including pitch and loudness.

The hypotheses about the similarity of sounds were as follows:

1- The ratings would be higher for adjustable complex tones than for adjustable pure tones (in accord with Lazard et al, 2012).
2- In each experiment, the ratings for low frequency would be higher than for high frequency (due to higher probability of neural survival expected in the apical region of the cochlea).
3- In each experiment and for each frequency, the ratings of soft sounds would be higher than for loud ones (due to less current spreading, electrode activation spreading and spectral spreading at the softer level).

The hypotheses of experiments A-1 and A-2

In this experiment, current spreading was studied. It was hypothesized that the current can spread to both sides of the tested electrode and stimulate neurons on both sides for loud sounds. If the neurons coding pitch at soft levels and the neighbouring neurons are all in good condition, then even with increased intensity there should be little or no change in the perceived pitch. At the loud level, the dominant neurons which are coding pitch would be the same target neurons of the soft level. This is also the case when the neighbouring neurons are in a worse situation than the targeted neurons. If the neurons on either side of the target are in better condition in terms of survival and number, they would dominate the coding of pitch at loud levels. This means that if the lower frequency region has better survival than the targeted neurons, lower pitch would be perceived with increases in intensity. Two electrodes were selected: one was the most apical electrode which corresponded to the best residual hearing in the non-implanted ear, and the other was an electrode with centre frequency up to 1000 Hz which corresponded to the highest frequency with residual hearing thresholds of less than 90 dB HL in the non-implanted ear.

Hypotheses:

1- The pitch matches for the apical and basal electrodes would be in the range predicted by the Greenwood function.
2- Pitch would decrease when intensity increased at the more basal electrode (because of the greater probability of neural survival in the lower frequency region of the cochlea) while there would be no change in pitch with intensity at the most apical electrode
3- The similarity ratings at each frequency, and the intensity level in this experiment would be higher for A-2 than A-1 as a result of the possible similar quality of a pulse train to a complex tone in the non-implanted ear rather than a tonal quality.

The hypotheses of experiments B-1 and B-2

Electrode activation spreading for pure tones was studied in this experiment. Two tones were chosen: 250 Hz, which is mapped to the most apical electrode 22 by the CI sound processor, and either 1000 Hz (if the hearing threshold was 90 dB HL or less in the non-implanted ear) or 750 Hz. These frequencies were mapped to electrodes 16 or 18 respectively by the CI sound processor. For the low frequency tone, electrode activation can only spread to the neighbouring more basal electrodes at loud levels but neurons of both sides are involved in coding of pitch due to current spreading. If the density of survival of neurons at the basal side of the target neuron at soft levels is better, there would be an increase in pitch due to both current and electrode activation spreading in the same direction. For the high frequency tone, there are neighbouring electrodes on both sides of the target electrode that receive stimulation at loud levels as a result of electrode activation spread. Electrode activation happens symmetrically as shown in figures 2-3 to 2-8. Also, the neighbouring neurons on both sides of the target neurons are involved in coding of pitch due to current spreading. Since the probability of a higher density of surviving neurons is greater in the apical direction, and since electrode activation spreading can happen in both apical and basal directions, there is likely to be a decrease in perceived pitch at loud intensities. If the density of neurons is higher in the basal direction, there would be higher pitch at loud levels. If the density of the target neurons is higher than that of its neighbours, and the current spread and electrode activation are symmetrical, there may be no change in perceived pitch at loud levels.

Hypotheses:

1- The pitch matches for the low and high frequency tones would be in the range predicted by the Greenwood function for the corresponding apical and basal electrodes.
2- There would be no change in the perceived pitch of the low frequency tones at loud levels while pitch would decrease when intensity increased for high frequency tones.
3- The similarity ratings at each frequency and intensity level in this experiment would be higher for B-2 than B-1

The hypotheses of experiments C-1 and C-2

Spectral spreading was studied in this experiment. Since the stimulus type was a piano note, it was expected to have several harmonics represented at soft levels, and each harmonic stimulating its target neurons. As the resolution of the harmonics is important for pitch perception, the ideal situation is that at loud levels, the same set of electrodes receives stimulation. However at loud levels, more harmonics rise above threshold in the sound processor, electrode activation spread happens for each harmonic, and current spread occurs for each active electrode (see figure 2.9).

Low frequency piano note: For the fundamental frequency of 250 Hz which corresponds to electrode 22, the electrode activation spread happens only in the basal-ward direction while for higher harmonics it happens in both directions on both the basal and apical sides. In addition, there is current spreading which happens in both directions. The low frequency piano note has more harmonics in the low frequency region, which may have better neural survival. Since the harmonics are represented at basal-ward positions and electrode activation spreads to both sides for all harmonics except the fundamental frequency, higher pitch is expected at loud levels. This is because at soft levels, only the fundamental frequency and lower harmonics have enough energy to stimulate their corresponding neurons, but at loud levels, higher harmonics also receive enough energy to play a role in the coding of pitch. However, the higher harmonics may stimulate regions of lower density neural survival, and the probability of stimulation of neurons due to current spreading is higher on the apical side of each harmonic. Therefore, depending on the density of neural survival along the cochlea, all scenarios are possible: decrease, increase and no change in perceived pitch at loud levels.

High frequency piano note: As for the low frequency piano note, the pitch may be unchanged or either increase or decrease at loud levels.

Hypotheses:

1- The perceived pitch of low frequency piano notes presented to the implanted ear would be higher than for pure tones or the corresponding single electrode stimuli at both loud and soft levels because of the presence of the high frequency harmonics.
2- There would be no change in the perceived pitch of low frequency piano notes with increase in intensity while there would be a decrease in the perceived pitch of high frequency piano notes with increases in intensity
3- The similarity ratings at each frequency and intensity level in this experiment would be higher for C-2 than those in C-1

Materials and Methods

Pitch matching tasks were used to assess all above-mentioned hypotheses. In all the matching tasks, an adjustable sound (presented to the non-implanted ear) was matched to a reference sound (presented to the implanted ear). The effect of intensity and quality of sound was investigated by specific consideration of current spreading, electrode activation spreading and spectral spreading. Therefore, three types of reference sounds were presented to the CI ear of bimodal listeners: single electrode stimuli (used in experiment A-1 and A-2), pure tones (used in experiments B-1 and B-2), and piano notes (used in experiments C-1 and C-2). The reference sounds were presented at two levels of soft and loud to investigate the effect of intensity.

The difference between the reference sounds was designed to show the effect of quality of sound on pitch perception. To investigate this effect further, two different types of adjustable sounds were used. In experiments A-1, B-1 and C-1, the adjustable sounds were pure tones, and in experiments A-2, B-2 and C-2, the adjustable sounds were complex tones.

Between-modality electric-acoustic pitch matching

The matching of pitch and changes in pitch using residual hearing in the non-implanted ear gives an opportunity to learn more about the perception of pitch in CI users. This is why many authors have tried to determine the actual place of stimulation of CI electrodes using between-modality pitch matching experiments (Blamey, Dooley et al. 1996, Baumann and Nobbe 2006, Dorman, Spahr et al. 2007, Nardo, Cantore et al. 2007, Baumann, Rader et al. 2011) There are several criticisms about using the matching procedure in pitch perception.

One of these criticisms is related to the lack of enough residual hearing in the non-implanted ears which may make the results of pitch matching experiments unreliable. The large variability that has been observed is attributed to the limited ranges of available frequency for matching pitch and poor frequency selectivity of residual hearing in the non-implanted ears (Green, Faulkner et al. 2012). Despite good frequency selectivity in profound low frequency hearing losses, variability has been observed in an experiment of electric-acoustic pitch matching when the non-implanted ear had normal hearing with all three procedures of adaptive, constant stimuli and adjustment (Faulkner, Rosen et al. 1990, Faulkner, Ball et al. 1992), (Carlyon, Macherey et al. 2010b). Therefore, frequency selectivity, limited frequency range, and hearing thresholds do not explain all of the variability in between-modality pitch matching experiments (Green, Faulkner et al. 2012). There must be other factors that contribute to the observed variability, including the difficulty of matching a pure tone to a non-pure-tone stimulus, inter-subject variability in electrode placement, variability in neural survival, and plasticity changes in the auditory system before and after cochlear implantation.

Another criticism of electric-acoustic pitch matching is that when pulse trains stimulate the neurons with fixed high rate, the elicited pitch is perceived through place coding while low frequency sounds presented to the non-implanted ear are perceived through both temporal and spatial coding. As Tong, Blamey et al. (1983) showed, the quality of pitch perceived through place coding is different from that of temporal coding. This difference in quality may hinder reliable electric-acoustic pitch matching and may be a cause of variability. In one study by Carlyon, Macherey et al. (2010b) in which both the stimuli presented to the implanted and non-implanted ears had similar low rate (therefore had similar temporal cues), large variability in matched pitches was observed. This shows that the similarity of temporal cues in both ears does not guard against large variability in such experiments.

Despite the afore-mentioned criticisms, when a combination of different reference and comparison sounds are selected and some precautions are taken in the interpretation of the data, between modality matching may be useful in pitch perception studies. It has been suggested that between-modality matching might be useful in the investigation of systematic pitch changes with intensity, which was the aim of the current experiments (Shannon 1983, Townshend, Cotter et al. 1987). In contrast, matching tasks might also be applied more easily for people without a history of music training than some other pitch perception tests which rely on musical knowledge (Pijl 1997). Therefore, pitch matching between electric and acoustic hearing was used in the following experiments which were performed with relatively untrained listeners.

In the experiments which are described later, different combinations of reference and adjustable sounds were used and some precautions were exercised in order to make the interpretation of the data more reliable.

In experiments A to C, the task was to adjust the pitch and intensity of an adjustable acoustic sound to a reference electric sound. There are different theories about the perception of pitch in the literature and various factors may play a role in pitch perception.

Mainly pitch is the subjective correlate of the fundamental frequency [F0] of sound. In these experiments, the measure of pitch was the quantitative value of the matched fundamental frequency selected by the participants in the non-implanted ear.

The differences between experiments A-1, B-1 and C-1 were in the different types of reference sounds and the CI maps which were used in these experiments. In experiments A-1, B-1 and C-1 the adjustable pure tones were matched to the reference sounds.

Experiment A: electro-acoustic pitch matching for a single electrode

Experiment A is called the "single electrode" condition throughout this chapter because there was no activation on other electrodes except the tested electrode. Therefore this condition provided an opportunity to assess the effect of current spreading on electro-acoustic pitch matching with increases in the level of intensity. The stimuli were generated by direct audio input of a pure tone into the CI sound processor, and some manipulation in the map of CIs was required to enable the sound processor to maintain the whole stimulation on one single electrode at high intensity.

It was assumed that bimodal listeners in this study would have limited residual hearing in the low frequency region. The matching was done in a range of frequencies in which the participants could hear the stimuli both through CI and HA. Two electrodes from the low frequency region were selected to be stimulated based on the availability of residual hearing in the opposite ear. One of the electrodes was the electrode with the lowest centre frequency (most apical electrode). The other electrode was selected according to the highest frequency in the non-implanted ear with a hearing threshold of 90 dB HL or less (either 750 Hz or 1000 Hz).

Since each electrode covered a range of frequencies, the centre frequency of each electrode filter was the benchmark for selecting the electrode. The formula for the calculation of centre frequency was (Taylor and Huang 1997):

$$Fc = sqrt\ (Fl * Fh)$$

Fc is the centre frequency while Fl and Fh stand for lower and higher cut-off frequencies of the corresponding bandpass filter respectively. Electrode number 22, which is used for sounds with the lowest frequency, was selected as one of the electrodes. A 250 Hz pure tone was used to stimulate this electrode. The other selected electrodes were either electrode number 16, which represented a 1 kHz pure tone, or electrode number 18 which covered 750 Hz.

The reference sound

The reference sounds were 250 Hz, 750 Hz or 1 KHz single electrode pulse trains with durations of 710 msec, and 10 msec rise and 200 msec fall times. These sounds were presented to the sound processor using direct audio input at intensity levels which in half of the trials elicited a soft loudness and in the other half a loud loudness. The reference sounds were kept focused on a single electrode for soft and loud levels of intensity. This is why this condition is called the "single electrode" condition. This was done by manipulating the CI map of every participant, which will be discussed in detail later in this chapter. Since different people have their own unique perception of the intensity of sound, soft and loud sensations for each participant were determined individually using a 7-step scale with steps from "inaudible" to "too loud". The soft level for the tests was "soft but audible" and the loud level was "loud but comfortable". The reference sounds were always presented to the ear with a CI through Direct Audio Input (DAI).

Experiment B: electro-acoustic pitch matching for a pure tone

Experiment B was designed to show how the perception of pitch of a pure tone could be changed when both current and electrode activation spreading took place. At high levels of intensity, more than one electrode might be stimulated (electrode activation spreading) along with an increase in the number of neurons activated by each electrode (current spreading).

The reference sound

The reference sounds of experiment B were pure tones at low (250 Hz) or high frequencies (750 or 1000 Hz), which were presented at soft and loud levels via the CI sound processor. The temporal characteristics of these pure tones were completely similar to the pulse trains of experiment A except that these pure tones could stimulate more than one electrode at higher intensity levels. The reference sounds were presented to the implanted ear through DAI. Unlike experiment A, the reference stimuli were presented to a sound processor which was fitted with the participant's everyday map.

Experiment C: electro-acoustic pitch matching for a piano note

The reference stimuli in this experiment were piano notes presented via the CI sound processor. The piano notes were generated with a high quality sampler of an acoustic piano (Ableton Live 8). The sound processors of CIs pick up the fundamental frequency and overtone harmonics of musical notes (by filtering the sound) and represent them on different corresponding electrodes. For complex harmonic sounds, more than one electrode is activated, even at low intensities, because of the harmonic representation of sounds (spectral spreading). In addition, at high input levels, some electrodes next to the selected electrodes and more neurons can be stimulated because of current and electrode activation spreading. Therefore, experiment C was designed to assess the combined effects of spectral spreading plus electrode activation spreading, plus current spreading.

The reference sound

The reference sounds of this experiment were piano notes with 11 harmonics. The fundamental frequencies (F0) of the stimuli were 250 Hz in half of the trials and 750 or 1000 Hz in the other half. Like experiments A and B, the stimuli had duration of 710 msec and 10 msec rise and 200 msec fall times. They were presented to the implanted ear through DAI. The piano notes were presented in the levels of intensity which were rated as soft and loud by the participants. All the reference stimuli were presented through an everyday CI map.

Adjustable sound in experiments A-1, B-1 and C-1

The adjustable sounds were pure tones presented to the non-implanted ear through an insert ear phone. The participants' HAs were not used in the experiments. The frequency and intensity of the adjustable sounds were determined by the participants. Since the different ranges of sounds in the non-implanted ears for matching could introduce some bias on the matched frequency (Carlyon, Macherey et al. 2010b, Green, Faulkner et al.

2012), a wide but similar range of frequencies was made available to the participant for each trial. They could change the frequency of the sounds in a range from 80 to 2000 Hz on a logarithmic scale. In addition, the starting frequency of the adjustable sounds was randomized for each trial. The level of intensity of the adjustable sounds could be changed in steps of 0.5 dB. Since different participants had different degrees of hearing loss at different frequencies, the required gain to compensate for the hearing loss at each frequency was added to the adjustable sound before outputting it to the non-implanted ear. The required gain was calculated based on the NAL-RP hearing aid fitting formula. This formula is good for the estimation of the required gain for severe-to-profound hearing loss at each frequency in the non-implanted ear (Dillon 2012). Therefore the participants were able to hear the sounds at both soft and loud levels in the non-implanted ear while their hearing aids were put aside and were not used in the pitch matching procedures. Thus all the participants were fitted with linear amplification and there was no difference in terms of the type of sound processing strategy used in the non-implanted ears.

The pairs of experiments A-1 and A-2, B-1 and B-2, and C-1 and C-2 were similar in all aspects except that the adjustable sounds in experiment A-2, B-2 and C-2 were complex tones.

Adjustable sound in experiments A-2, B-2 and C-2

The adjustable sounds in these three experiments were complex-tone sounds with 11 harmonics which passed through a fourth-order Butterworth filter whose centre frequency was 1.64 times the fundamental frequency. The Butterworth filter is designed to have as flat a frequency response as possible in the passband (Butterworth 1930). It is also referred to as a maximally flat magnitude filter. The Q factor of the filter was 13.4, which was the preferred Q factor in a previous study of bimodal pitch matching (Lazard, Marozeau et al. 2012). Q factor is a parameter that describes the damping characteristics of a filter, or equivalently, characterizes a filter's bandwidth relative to its centre frequency. Higher Q indicates a lower rate of energy loss relative to the stored energy of the resonator or filter. It means that the oscillations die out more slowly (Harlow 2004). In addition, the starting phases of the harmonics of the complex tone were randomized. The starting frequencies of the adjustable sounds were completely randomized as well at the beginning of each pitch matching trial. The complex adjustable sound was presented to the non-implanted ear through an insert phone. The participants' HAs were not used in the experiments. Figure 2-10 shows the spectrum of the complex sound.

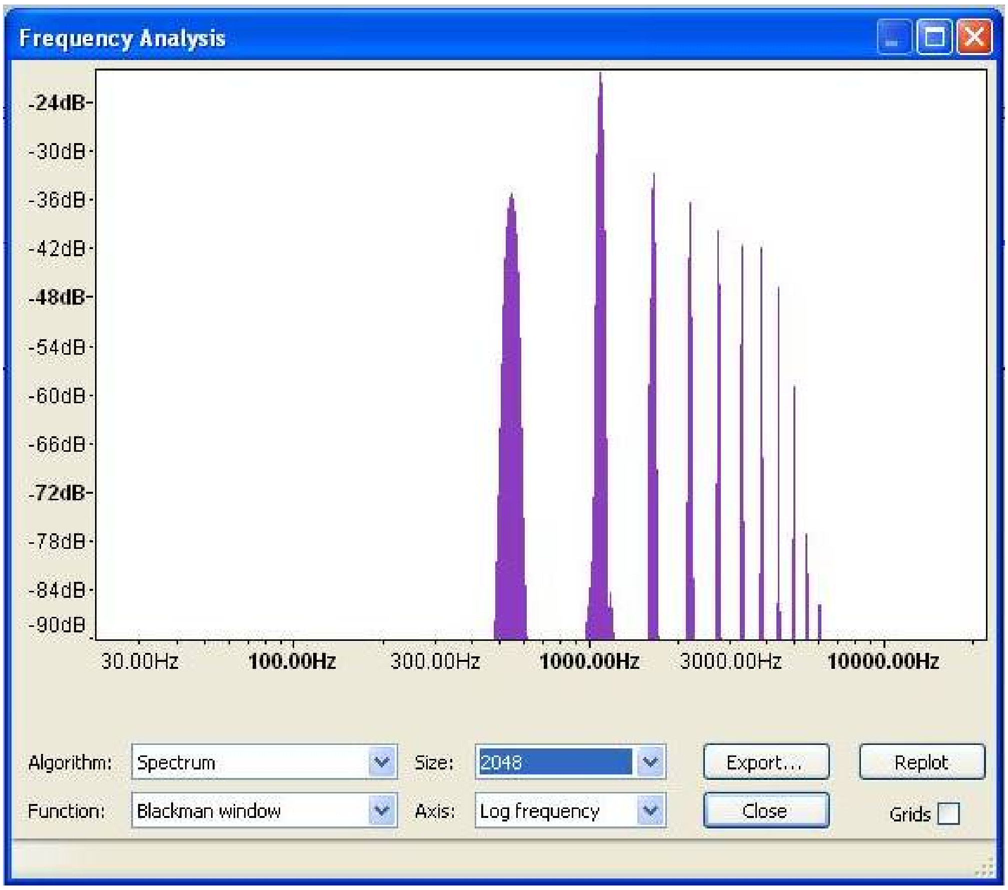

Figure 2-10: Spectral representation of the complex adjustable sound

This figure shows the fundamental frequency and higher harmonics (spectral representation) of the complex sound when it was passed through a filter with centre frequency of 1.64 and Q factor of 13.4. The horizontal axis shows the frequency of each harmonic on a logarithmic scale. The vertical axis shows the amplitude of each harmonic in dB of attenuation from the maximum output of the sound card.

Both the reference and adjustable sounds were made and presented by MAX/MSP 6 (Cycling 74 Co.). MAX/MSP is a software programming package for creating musical sounds. It also enabled the experimental interface and data collection after each matching trials.

CI Sound processor

For ethical reasons, the experimenter was not allowed to change any parameters of the participants' sound processors. Therefore, the latest map of each participant was received from the clinic and the map was recreated and programmed onto an experimental Nucleus Freedom™ sound processor.

The Freedom Sound Processor consists of a processing unit and coil. Sounds can be received in Freedom processor through the microphones, the built-in telecoil, an accessory or a mix of microphone sounds and sound from the built-in telecoil or an accessory. The sound is coded by the processing unit and transmitted through the coil to the internal receiver-stimulator and delivers the decoded sounds to the electrode array of the CI. The implant's electrodes stimulate the cochlea's hearing nerve fibres, which relay the signals to the brain to produce hearing sensations. There are several pre-processing program options in this processor to improve the quality of sound signals. These are Beam, Whisper, ADRO and Autosensitivity. Beam allows users to focus on the sounds coming from the direction in which they are looking. Whisper is better able to detect soft sounds in quiet situations. ADRO makes automatic adjustments where there are large changes in sound between loud and soft. Autosensitivity adjusts the sensitivity level of the microphone automatically for comfortable listening in different environments. (Cochlear 2014). During the pitch matching procedures, the pre-processing options were turned off and all reference signals were presented through the direct audio input to the sound processor in order to provide complete control over the amplitude of signals presented to the sound processor.

Cochlear implant map

CI map in experiments A-1 and A-2 (single electrode map):

A map was created so that it prevented electrode activation spreading. In this map, there were just three active electrodes and all other electrodes were deactivated. The whole range of frequencies was reallocated to these three electrodes. One of these electrodes was the electrode with the lowest centre frequency [electrode number 22]. Another was electrode number 18 or 16 with centre frequency close to 750 Hz or 1000 Hz respectively according to the participants' residual hearing. To prevent stimulation from spreading, one electrode remained active between these two electrodes, but with T- and C- levels of 0 current units (CU). Even if this intermediate electrode was activated, there would be no stimulation because with T and C thresholds of 0 CU, stimulation did not occur. In addition, due to the new frequency allocation subsequent to deactivating the electrodes between this electrode and the other two electrodes, the spread of electrode activation could not occur in practice. This map had C levels for the two active electrodes that were 10 CU higher than the everyday map to compensate for the loudness summation due to the use of more active electrodes in the everyday map. This map was used just for the single electrode experiments (A-1 and A-2), and for this reason it is called the "single electrode" map.

CI map in experiment B-1, B-2, C-1 and C-2:

For experiments B-1, B-2, C-1 and C-2 the CI map was the map used by the participants in everyday life except that its pre-processing programs (e.g. Whisper, ADRO, etc.) were disabled. This map was recreated and written on a Freedom sound processor based on each participant's latest CI map.

Rating scale

Although the participants were asked to spend enough time to reach the best possible match, it was still possible that even upon final best matching, two sounds were not similar. To quantify the degree of similarity between the reference and adjustable sounds, a rating scale was made available to the participants on which to rate their similarity judgments about the final best matches. This rating scale was a line representing very similar at one end and very dissimilar at the other end. After each trial the participant was asked to point on the line representing the similarity of the matched adjustable sound and the reference sound, taking into account all aspects of the sounds including both pitch and loudness. The analyses of ratings could show for each type of sound, which adjustable sounds selected in the final matching were most similar to the reference sounds.

Procedure for all experiments

After listening to the reference sound, the participants would start changing two dials. The participants were asked to match the loudness of the adjustable sound to the loudness of the reference sound. In most studies of pitch perception in CI users, loudness was roved or balanced. Since the literature review indicated that loudness could affect the perception of pitch, the participants were asked to change both pitch and loudness to find the best matches. In this way, the best pitch matches were yielded as a result of the interplay between loudness and pitch aspects of the sounds. After matching the loudness aspect, the participants started changing the pitch dial to match the pitch of the adjustable sound to the pitch of the reference sound. The third step was to adjust pitch and loudness dials together if the participant thought there was some fine-tuning needed for the best matching.

Then, two following questions were asked of the participants: “Is the loudness of the two sounds matched?” and “Is the pitch of the two sounds matched?” These questions were designed to test the reliability of each matching and also help the participants to pay more attention to the matching aspects of the experiment (i.e. pitch and loudness) and to try to pick the most similar adjustable sound for the reference sound. Another benefit of these questions was that they let the experimenter know about potential reasons for dissimilarity.

When the experimenter was satisfied that the best match had been found, the participant performed the similarity rating.

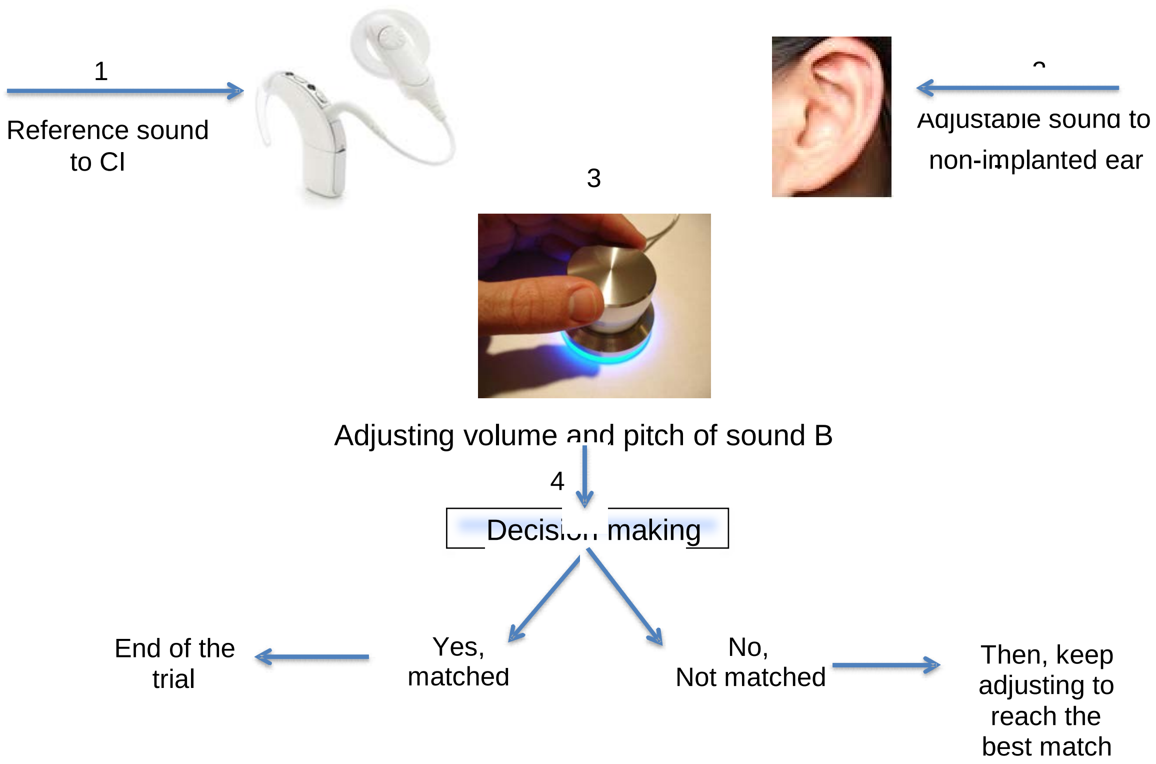

Figure 2-11: steps of the experiment

This schematic figure represents the steps which each participant had to take to do a trial. Each trial was started by a sound which was sent to the CI ear and another sound to the non-implanted ear. After that, the participant changed the intensity and fundamental frequency of the sound in the non-implanted ear by turning the intensity and frequency knobs. If, after this change, the two sounds in the two ears were matched, it was announced as the best match point by the participant. Otherwise the participant had to repeat these steps to reach the best match point.

To increase the reliability of the final best match, the frequency selected by the participant was changed and the participant had to indicate the direction of this change in reference to the matching frequency. If the participants correctly judged the direction of pitch change, this was an indication of the reliability of the final matching. To answer the hypotheses about all the combination of reference and adjustable types, the participants were required to do the tests across 3 sessions with one week between sessions. Each session took 1.5 hours.

Equipment for all experiments

Both reference and adjustable sounds were generated and output through a Motu S PCI-424 Audio Card, USA. The reference sound was presented to the Freedom sound processor by a DAI cable approved by Cochlear Ltd. for Freedom sound processors. This cable was attached to the bottom of the sound processor and delivered the sounds directly. During programming of the Freedom sound processor, the DAI mode was activated.

The adjustable sounds were presented to the non-implanted ear with a 3A E.A.R gold insert phone (Etymotic Research, Inc, USA) with a flat frequency response up to 10 KHz.

Two dials, one for changing fundamental frequency and the other one for loudness adjustment were used (PowerMate 3.0, Griffin Technology, USA). Figure 2-12 shows an image of the knobs.

Figure 2-12: the knob for matching

There were two knobs, one for changing the frequency and the other for changing the intensity of the Adjustable sounds. Both knobs had similar appearance.

The order of presentation

Each experiment was repeated three times. The order of experiments could induce a learning effect on the matching result. Therefore, a Latin Square table was followed for the order of presentation. Each table had three columns because each experiment was repeated three times. One example of a Latin square is shown below in table 2-2.

Order of presentation	First repetition	Second repetition	Third repetition
1	A-1 or A-2	C-1 or C-2	B-1 or B-2
2	B-1 or B-2	A-1 or A-2	C-1 or C-2
3	C-1 or C-2	B-1 or B-2	A-1 or A-2

Table 2-2: One example of a Latin square table which was used to assign the order of experiments

Since full randomization was not possible, the order of experiments was assigned to the participants by Latin squares. By following Latin square tables, the bias effects due to the order of the experiments were removed when the data were averaged over repetitions.

Statistical analyses for pitch matching and rating

There were three types of reference stimuli (one Reference type per experiment). Since the CI maps had to be changed and individualised for each experiment, it was not possible to randomise the assignment of Reference type from one trial to the next trial. Because of this, there were three blocks. Each block was assigned to a Reference type.

Within each block, two frequencies, one high and one low, were tested. Each frequency was tested at two levels of intensity: soft and loud. Each level of intensity was presented to the participants in two conditions [timbre of the Adjustable sounds]: One when the adjustable sounds were pure tones and the other when the adjustable sounds were complex tones. Each block was tested three times. The assignment of reference frequency, intensity and conditions was completely randomised within each block (experiment).

In summary, 8 data points in each block, three stimulus types and 3 repetitions and 72 data points in all three blocks were collected from each participant.

$$8\ Block\ data\ points = 2 \text{ frequencies} * 2 \text{ intensities} * 2 \text{ conditions}$$

$$Each\ person\ data\ points = 3\ Reference\ types * 3\ repetions * 8\ Block\ data\ points$$

Each of the blocks (experiments) were repeated three times (three repetitions) in an order determined by the Latin squares.

Although both types of adjustable sounds were tested in the same blocks, the results are considered as separate experiments in Chapters 3 and 4 for clarity.

Nested analysis of variance (ANOVA) was used to assess the above-mentioned experiments. The data were analysed based on their frequency. Within each frequency, the data were analysed based on level of intensity. Within each level of intensity, the data were assessed according to condition. The literature review indicated large individual differences among people in pitch perception. In addition, different participants of these experiments might have different neural survival, electrode-neuron positioning and electrode insertion depth which could not be examined in these experiments. Since the inter-subject variability cannot be ignored the participant was considered as an independent factor which could account for some portion of the variability in the collected data.

In the ANOVA table, in addition to the main effects of the factors, two-way interactions between each pair of factors, three-way interactions among each group of three factors, four-way interactions among each set of four factors, and the five-way interaction of all factors are shown in Table 2-3. Whenever there was a significant effect in the ANOVA, Tukey's post-hoc analysis was done to identify which levels of a factor reached statistically significant difference. Tukey's method compares the means for each pair of factor levels using a family error rate (often called family-wise error rate) to control the rate of type I error. The family error rate is the probability of making one or more type I errors for the entire set of comparisons. Tukey's method adjusts the individual confidence level, based on the chosen family error rate (Howell 2010).

Variables
Reference type
Participant
Frequency
Intensity
Adjustable type
Reference type*Participant
Reference type*Frequency
Participant*Frequency
Reference type*Intensity
Participant*Intensity
Frequency*Intensity
Reference type*Adjustable type
Participant*Adjustable type
Frequency*Adjustable type
Intensity*Adjustable type
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Reference type*Participant*Frequency*Adjustable type
Reference type*Participant*Intensity*Adjustable type
Reference type*Frequency*Intensity*Adjustable type
Participant*Frequency*Intensity*Adjustable type
Reference type*Participant*Frequency*Intensity*Adjustable type
Residual
Total

Table 2-3: the output of the ANOVA analysis

"The matched frequency" and "rating of similarity" were the dependant variables. The former is assumed to be a physical correlate of pitch perceived by the participants and the latter is a quantitative measurement of the participants' judgment about the similarity between the reference and adjustable sounds in the selected matches.

Participants

Twelve bimodal cochlear implant users (4 females and 8 males) participated in electro-acoustic pitch matching. These people were selected from the number of people who satisfied the criteria for inclusion of the experiments. Each participant responded to an invitation letter from the Cochlear Implant Clinic of the Royal Victorian Eye and Ear Hospital (RVEEH). This number of people was a clinically feasible number for the experiment.

The participants had an age range from 61 to 87 years with an average of 72.75 years. They lost their hearing due to various etiologies: unknown (4 people), noise-induced hearing loss (3 people), age (2 people), hereditary factors (2 people), and Otosclerosis (1 person). They had an average duration of deafness of 30.8 years before implantation with a range of 10 to 55 years. They had also used their hearing aids for an average of 18.3 years with a range of 2 to 55 years at the time of the experiments. All of the participants were accustomed to their CIs (with average experience of 4.1 years and a range of 3 to 7 years). None of them had been a musician or had special music training before or after their hearing loss, and they were not able to play any type of instrument.

To be included in these studies, every subject needed to have post-lingual deafness and use a CI. They also had to have measurable hearing in the frequency range from 250Hz to 1 KHz with thresholds lower than or equal to 90 dB HL at 250 Hz and 750 Hz or 1 KHz. El Fata, James et al. (2009) suggested that a bimodal CI configuration would improve the perception of music for CI users with average hearing thresholds of 85 dB or better in the frequencies of 125 to 1000 in the non-implanted ear. However, some published data reported no systematic relationship between the thresholds in the audiometric evaluation and the extent of benefit from the binaural scheme (Litovsky, Johnstone et al. 2006, Green, Faulkner et al. 2012) and pitch perception (Santurette and Dau 2007). Moreover, even in cases of profound hearing loss, some frequency selectivity was observed at low frequencies (Faulkner, Rosen et al. 1990). Therefore, the threshold of 90 dB was considered suitable for finding people with a low probability of dead regions at low frequencies in their non-implanted ears. In addition, the practical constraints of finding bimodal CI users did not allow us to apply a stricter criterion for their inclusion in the study. An important criterion was that the participants used their hearing aids and CIs together for at least 70% of the time. They were required to have at least 1 year of experience with both their HAs and CIs together, as it has been reported that binaural benefit is shown after one year of bimodal use (Vermeire and Van de Heyning 2009). Ten participants had full insertion depth of electrode arrays and the remaining two (S2 and S8) had partial insertion.

Residual hearing

The amount of residual hearing is shown in figure 2-13 for all participants in this study. The pitch matching test was done for all the participants at low and high frequencies. Low frequency stimulation for all of the participants was delivered to electrode number 22 (with centre frequency close to 250 Hz or its equivalent in MIDI number of 59). The high frequency stimulation was sent to the electrode with a centre frequency close to 1 kHz (or its equivalent in MIDI number of 83), provided that the participant had a hearing threshold below 90 dB HL at 1 kHz. Therefore, electrode 16 (with centre frequency close to 1 kHz) was selected to receive high frequency stimuli. Since S10 and S12 had hearing thresholds above 90 dB HL at 1 kHz, electrode number 18 (with a centre frequency close to 750 Hz or equivalent to MIDI number 78) received high frequency stimulation. In doing this, it was assumed that high frequency stimulation was being delivered to an electrode which was in contact with enough residual hearing to hear the sound. S2, with a nearly flat audiogram and thresholds around 55 dB, had the best residual hearing at both low and high frequencies. The participants' CIs had to be fitted with the ACE sound processor strategy, while they could have linear or nonlinear hearing aids. Also, a consent form was signed by all participants.

Tables 2-4 and 2-5 summarise the details of their CI maps. Participants S7 and S10 had only 4 and 2 maxima respectively because the high levels of stimulation needed to reach comfortable loudness required wide pulse width that were incompatible with high rates and larger number of maxima.

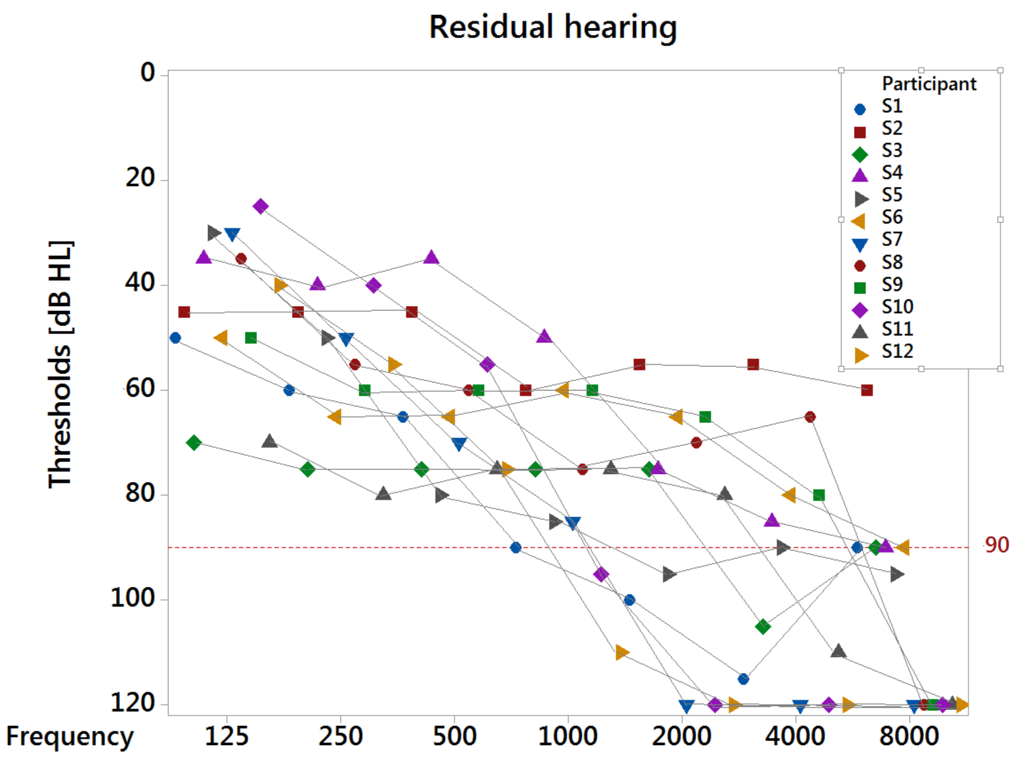

Figure 2-13: the participants' audiometric thresholds in the non-implanted ear

The vertical axis shows the thresholds of hearing in dB HL. The horizontal axis shows the tested frequency from 125 to 8000 Hz. The dashed line indicates 90 dB, which was the benchmark for selection of the electrode which would receive high frequency stimulation. Only S10 and S12 had thresholds above 90 dB at 1000 Hz.

Participant	Rate (pps)	No. maxima	Pulse Width (µs)	Loudness Growth	T-SPL	C- SPL	Dynamic Range (CL)	T-level (CL)	C-level (CL)	Tested electrodes	Number of active electrodes
S1	500	8	25	18	28	70	32	152	184	22	22
							45	150	195	16	
S2	500	8	25	20	25	65	25	146	171	22	19
							25	132	157	16	
S3	500	8	25	20	25	65	44	128	172	22	22
							50	129	179	16	
S4	1200	8	25	20	25	65	38	142	180	22	22
							62	110	172	16	
S5	900	8	25	16	25	75	26	177	203	22	22
							33	173	206	16	
S6	1200	8	25	16	25	75	53	136	189	22	22
							38	148	186	16	
S7	500	4	50	20	25	65	58	101	159	22	22
							68	105	173	16	
S8	900	8	25	20	25	65	42	110	152	22	20
							58	91	149	16	
S9	900	8	25	20	25	65	32	144	176	22	22
							37	130	167	16	
S10	900	2	200	16	25	75	84	88	172	22	22
							96	76	172	18	
S11	900	12	25	20	25	65	50	112	162	22	22
							34	113	147	16	
S12	900	8	37	16	25	75	27	138	165	22	22
							58	1110	168	18	

Table 2-4: the parameters of cochlear implant maps of different participants

Participant	Age	Etiology	Experience with CI	HL duration	Sound processing strategy	Electrode array	Bimodal experience	Stimulation mode)	PTA dB HL	Type of hearing aids
S1	71	unknown	3	55	ACE	Contour	3	MP1+2	68	Phonak
S2	76	Otos clerosis	5	48	ACE	Contour	5	MP1+2	50	Widex
S3	80	presbycusis	4	20	ACE	Contour	4	MP1+2	75	Siemens
S4	61	Unknown	4	38	ACE	Contour	2	MP1+2	41	Phonak
S5	70	NIHL	3	25	ACE	Contour	3	MP1+2	71	Phonak
S6	72	NIHL	3	27	ACE	Contour	3	MP1+2	75	Widex
S7	87	NIHL	5	10	ACE	Contour	2	MP1+2	68	Phonak
S8	68	hereditary	4	33	ACE	Contour	4	MP1+2	61	Phonak
S9	70	Unknown	5	27	ACE	Contour	5	MP1+2	60	Siemens
S10	76	hereditary	3	23	ACE	Contour	3	MP1+2	63	Starkey
S11	73	presbycusis	7	15	ACE	Contour	7	MP1+2	80	Siemens
S12	69	Unknown	4	49	ACE	Contour	4	MP1+2	75	Phonak

Table 2-5: information about the participants' CIs and HAs

Chapter 3: Bimodal pitch matching results

Results:

The results of experiments A to C are presented and discussed in this chapter. In all of these experiments, electro-acoustic pitch matching tasks were used to investigate the effects of the intensity and quality of sounds on the perceived pitch in CI users who have residual hearing in the non-implanted ears.

Shape of distribution and outliers:

"The matched frequency", which was the physical correlate of the perceived pitch, was recorded using a linear scale of Hz in a range from 80 to 2000 Hz. The frequency of a sound determines its pitch as perceived by a listener, and a frequency ratio of two is a perceived pitch change of one octave, no matter what the actual frequencies are. For instance if a sound of 100 Hz frequency is raised to 200 Hz, its pitch will rise one octave, and a sound of 500 Hz, when raised to 1000 Hz, will also rise one octave in pitch. This phenomenon can be summarized by saying that the pitch perception of the ear is proportional to the logarithm of frequency rather than to frequency itself. Therefore, it makes sense to express the frequency of a sound on a logarithmic scale. Since the perception of frequency is logarithmic (Moore 1998), the frequencies were transformed to MIDI notes prior to statistical analysis. Without this transformation the distribution of residual errors from ANOVA was not normal, while the normal distribution of errors is an assumption which should be met for using parametric statistical methods like ANOVA. In addition, pitch is an auditory sensation in which a listener assigns musical tones to relative positions on a musical scale based primarily on the frequency of vibration. Pitch is closely related to frequency, but the two are not equivalent. Frequency is an objective, scientific concept, whereas pitch is subjective. The results are described in MIDI note numbers to understand pitch perception from a musical point of view and in Hz to understand the physical correlate of pitch.

Figures 3-1 and 3-2 show the difference in the distribution of residual errors from the multifactorial ANOVA before and after transformation. By definition, residual error is defined as the difference between the observed response values and the fitted response values offered by a statistical model. Usually a normal probability plot is used to investigate the distribution of residual errors. If the residuals have a perfectly normal distribution, the data points on the probability plot will form a straight line. The reference line is the fitted cumulative distribution function based on the parameters estimated from the sample. The reference line [the blue line] indicates the ideal normal distribution. The departure from normality is shown by the departure of data points from the reference line (Howell 2010). The curvature in the distribution of residuals in Figure 3-2 indicates a non-normal distribution of the residuals for matched frequency on a linear scale. In the case of a non-normal distribution of the residual errors, transformation of the data before statistical analysis is recommended. Among many ways of transformation, a logarithmic transformation suits the present data not only because it solves the problem of the non-normal distribution, but it also makes the analysis more meaningful in terms of musical intervals or semitones. It should be noted that the MIDI note scale that is used in this thesis is a logarithmic transformation of the frequency scale, and one MIDI note is equal to one semitone. MIDI notes and semitones are used interchangeably in the following chapters as the MIDI note number provides a convenient numerical scale that is logarithmically related to frequency in Hz. Frequency in Hz was converted to MIDI number using the following equation. (Puckette 2007).

$$MIDI\ note\ number\ = 12\ log_2\left(\frac{frequency}{440}\right) + 69.$$

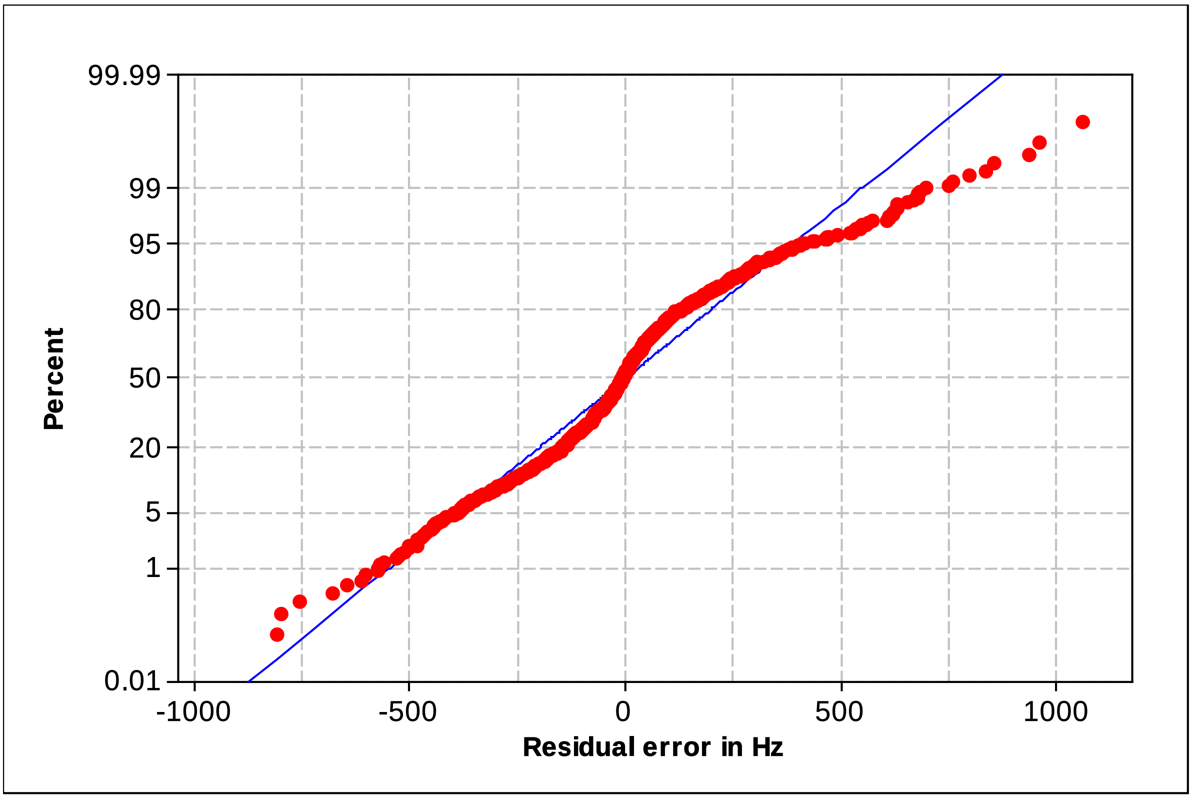

Figure 3-1: Distribution of residual errors before transformation

This figure represents the probability plot of the residual errors of the data as a percentage. The horizontal axis represents the error from 0 (no error). The vertical axis represents the cumulative percentage of errors. The departure from the reference line indicates the non-normal distribution of the residual errors for the untransformed frequency data.

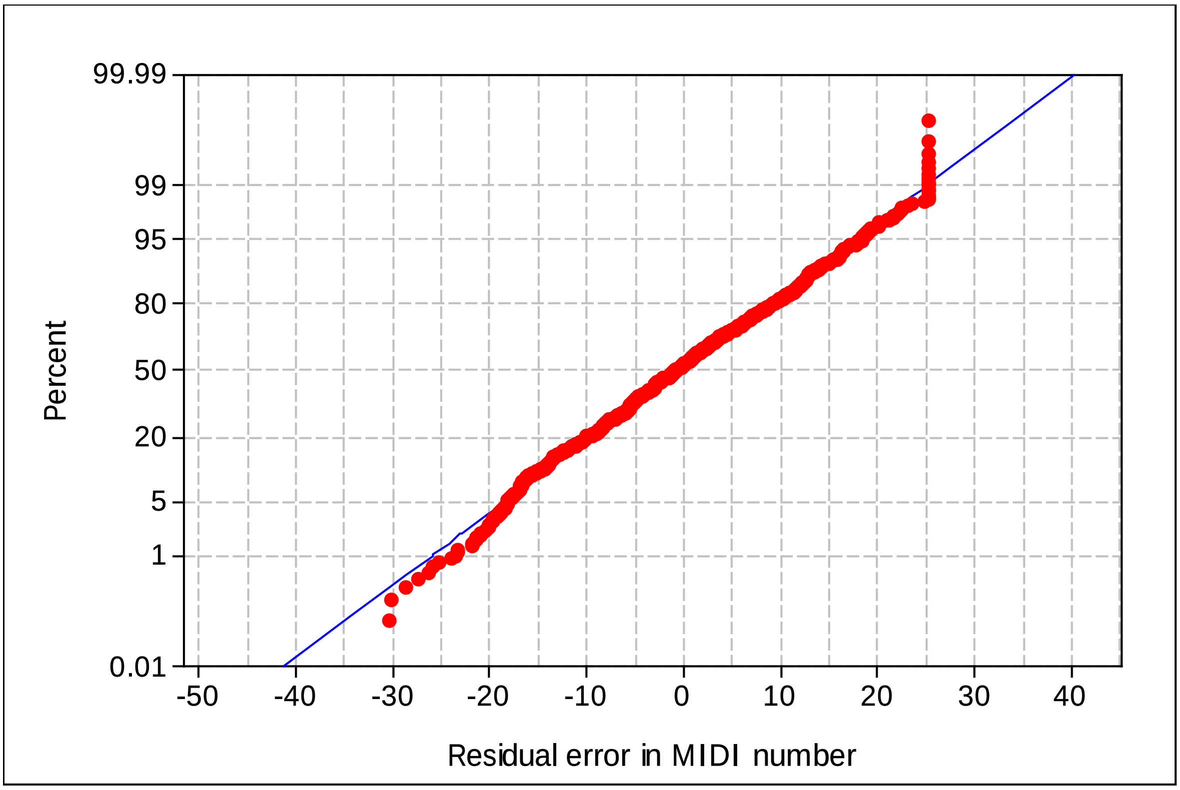

Figure3-2: Distribution of residual errors after MIDI note transformation

After transformation of the data, the departure from the reference line was much less pronounced.

The MIDI note transformation by itself did not remove the outliers. Therefore, the next step in the analysis was to consider outlying data points which could adversely affect the further analysis and conclusions. Before this, the possibility of mistakes in the data entry stage was double-checked and ruled out. Boxplots are standard tools to show possible outliers. Since there were few outliers (3 out of 864 data points) and all the outliers shown in figure 3-3 were within the range of the selected matched frequencies in the other experiments, none of them were removed. In fact, the effect of removing outliers in comparison with including them in the data set was negligible. Another advantage of the inclusion of those data was having a complete balanced data set which allowed a more powerful statistical analysis.

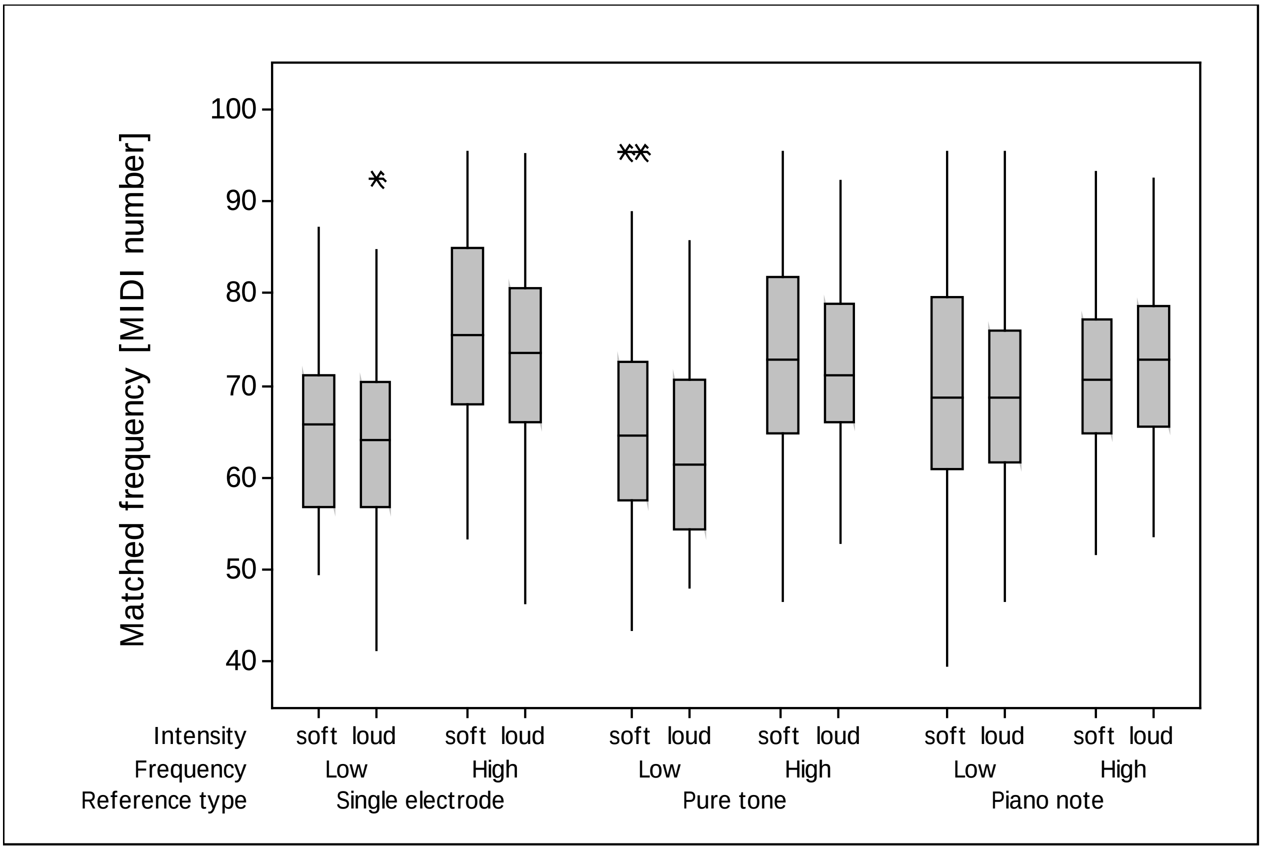

Figure 3-3: Summary of the distribution of all matched frequency data on the MIDI note scale

After the transformation of the frequencies to MIDI notes, the distribution of the matched frequency for each Reference Type at low and high frequencies and each level of intensity was depicted. There were three outliers which were included in the statistical analysis.

Analysis of the matched frequency data:

Table 3-1 shows the ANOVA of the transformed pitch matches for all six experiments A-1 to C-2 combined. This table will be used to assess the main hypothesis: "Perceived pitch of sounds presented to a CI will depend on the intensity and type of the sound."

The information derived from this table is a general description applicable to all experiments, although the results are also described for each experiment separately. This table shows the effects of different factors on "*the matched frequency*". The factors "*participant*", "*frequency*" and "*intensity*" show the effect of "*participant's performance*", "*frequency of the reference sound*" and "*intensity of the reference sound*" respectively. The statistically significant terms in the analysis are shown in bold type. Regardless of the type of adjustable sound, the respective mean and SD of the perceived pitch for single electrode was 69.6 ± 11 MIDI notes (455 Hz with a range from 214 to 855 Hz), for pure tone was 68.3 ±11 MIDI notes (422 Hz with a range from 223 to 797) and for piano note was 70.3 ±10.7 MIDI notes (473 Hz with a range from 246 to 880 Hz). The mean of the matched frequency for low frequency was 65.9 MIDI number (368 Hz) and for high frequency was 72.9 MIDI numbers (551 Hz), regardless of the type and intensity of Reference sounds and the type of Adjustable sounds.

Variable	df	MS	F ratio	P value
Reference type	**2**	**306.14**	**4.48**	**0.012**
Participant	**11**	**1135.49**	**16.6**	**<.001**
Frequency	**1**	**10495.6**	**153.44**	**<.001**
Intensity	**1**	**334.2**	**4.89**	**0.027**
Adjustable type	**1**	**8572.1**	**125.32**	**<.001**
Reference type*Participant	**22**	**130.11**	**1.9**	**0.008**
Reference type*Frequency	**2**	**1068.6**	**15.62**	**<.001**
Participant*Frequency	**11**	**578.21**	**8.45**	**<.001**
Reference type*Intensity	**2**	**208.27**	**3.04**	**0.048**
Participant*Intensity	**11**	**141.66**	**2.07**	**0.021**
Frequency*Intensity	1	0.06	0	0.976
Reference type*Adjustable type	2	70.06	1.02	0.36
Participant*Adjustable type	**11**	**205.67**	**3.01**	**<.001**
Frequency*Adjustable type	1	139.58	2.04	0.154
Intensity*Adjustable type	1	3.18	0.05	0.829
Reference type*Participant*Frequency	**22**	**116.24**	**1.7**	**0.025**
Reference type*Participant*Intensity	22	101.54	1.48	0.072
Reference type*Frequency*Intensity	2	90.14	1.32	0.269
Participant*Frequency*Intensity	**11**	**144.08**	**2.11**	**0.018**
Reference type*Participant*Adjustable type	22	44.39	0.65	0.889
Reference type*Frequency*Adjustable type	2	38.13	0.56	0.573
Participant*Frequency*Adjustable type	11	75.33	1.1	0.358
Reference type*Intensity*Adjustable type	2	20.19	0.3	0.745
Participant*Intensity*Adjustable type	11	57.65	0.84	0.597
Frequency*Intensity*Adjustable type	1	34.33	0.5	0.479
Reference type*Participant*Frequency*Intensity	22	72.9	1.07	0.381
Reference type*Participant*Frequency*Adjustable type	22	65.63	0.96	0.515
Reference type*Participant*Intensity*Adjustable type	22	47.88	0.7	0.842
Reference type*Frequency*Intensity*Adjustable type	2	141.72	2.07	0.127
Participant*Frequency*Intensity*Adjustable type	11	53.23	0.78	0.662
Reference type*Participant*Frequency*Intensity*Adjustable type	22	76.81	1.12	0.316
Residual	576	68.4		
Total	863			

Table 3-1: ANOVA of the matched frequency for all experiments

The independent variables were Reference type, Participant, Frequency, Intensity and Adjustable type. The dependent variable was the matched frequency.

The significant terms in the ANOVA with the largest F values in decreasing order were Frequency (as expected), Adjustable Type, Participant, Reference Type*Frequency, Participant*Frequency, Intensity, Reference Type, Reference Type*Intensity, Participant*Adjustable Type, Participant*Frequency*Intensity, Participant*Intensity, Reference Type*Participant, and Reference Type*Participant*Frequency. Individual differences are clearly important in understanding the pattern of results because there is a significant main effect of Participant and six out of eight significant interaction terms include Participant as a factor. Both Reference Type and Adjustable Type have significant interactions with Participant, so description of individual differences will be deferred until after the other main effects and interactions have been described. The effects of Frequency, Reference Type, Adjustable Type and Intensity, averaged over Participants are shown in figure 3-4. An important determining factor for the matched frequency was the Frequency of the reference sounds (df=1, F=153.44, $p < 0.001$). The Adjustable Type also had a very significant effect on the matched frequencies (df=1, F=125.32, $p<0.001$). Different participants selected different matched frequencies (df=11, F=16.62, $p < 0.001$) and the matched frequency was significantly different for different Reference Types (df=2, F=4.48, $p = 0.012$). Generally an increase in Intensity decreased selected matched frequency (df=1, F=4.89, $p = 0.027$).

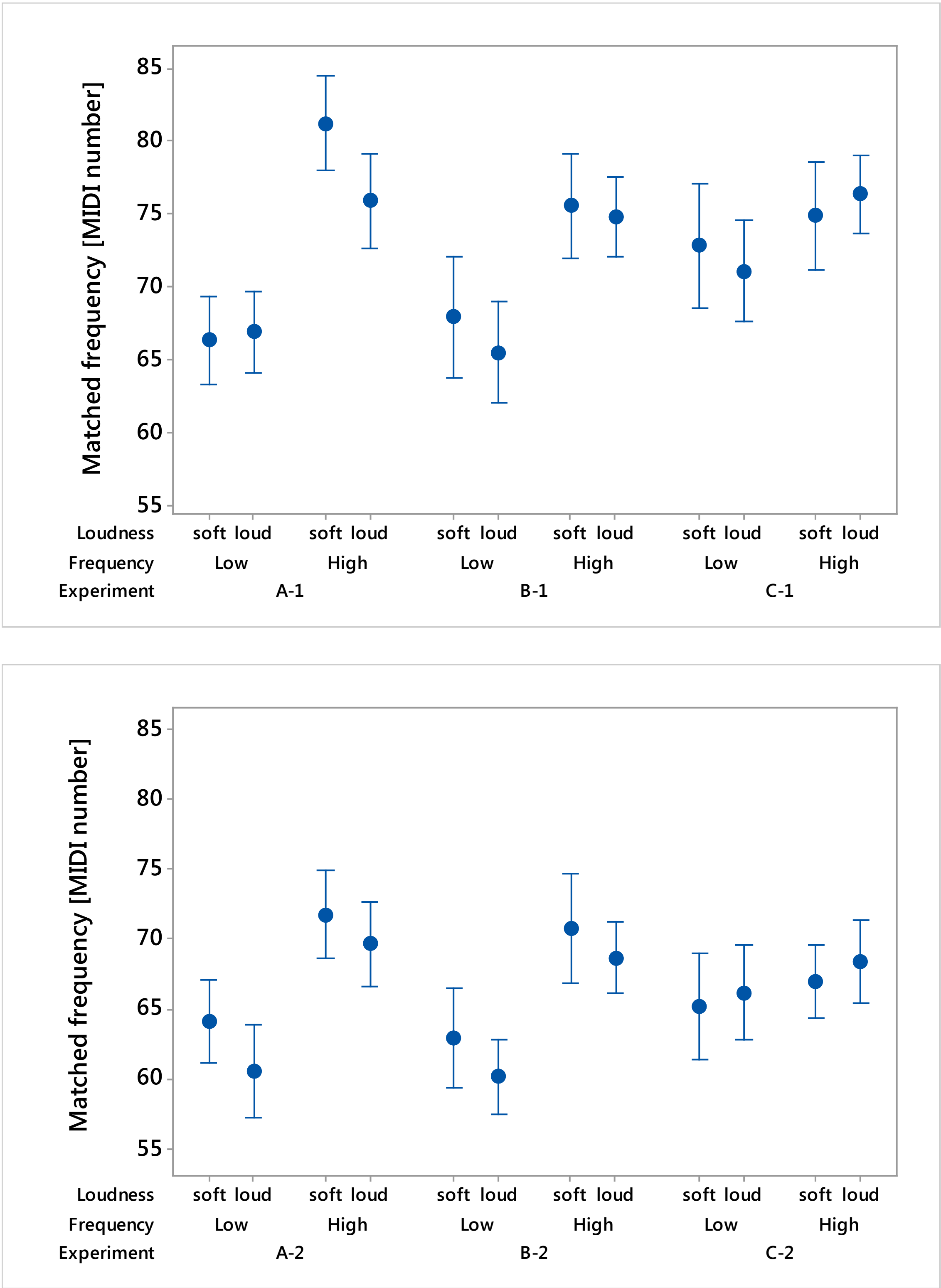

Figure 3-4: 95% confidence intervals of the matched frequency for experiments A to C at different frequencies and intensities, averaged over all participants.

The significant main effect of Frequency is obvious from the fact that the mean high frequency matches are above the low frequency matches for every Experiment. The significant interaction between Frequency and Reference Type is also clearly seen in figure 3-4 that shows that pitch differences between low and high frequency sounds are greater for the single electrode and pure tone stimuli in Experiments A-1, B-1, A-2, and B-2 than for piano notes in Experiments C-1 and C-2. This interaction is also illustrated by figure 3-5, which shows that, on average, the matched frequency for pure tone and single electrode experiments at low frequency were lower than that of the piano note experiments. Higher matched frequency was observed for the single electrode experiments than the piano note at high frequency. Figure 3.5 shows that the average difference in the matched frequency between low and high frequency reference stimuli (about 2.5 MIDI notes as shown on the vertical axis) is much smaller than the actual difference between the presented frequencies of the low and high frequency reference stimuli as shown on the horizontal axis (a difference of 19 MIDI notes for participants S10 and S12, and 24 MIDI notes for the other ten participants).

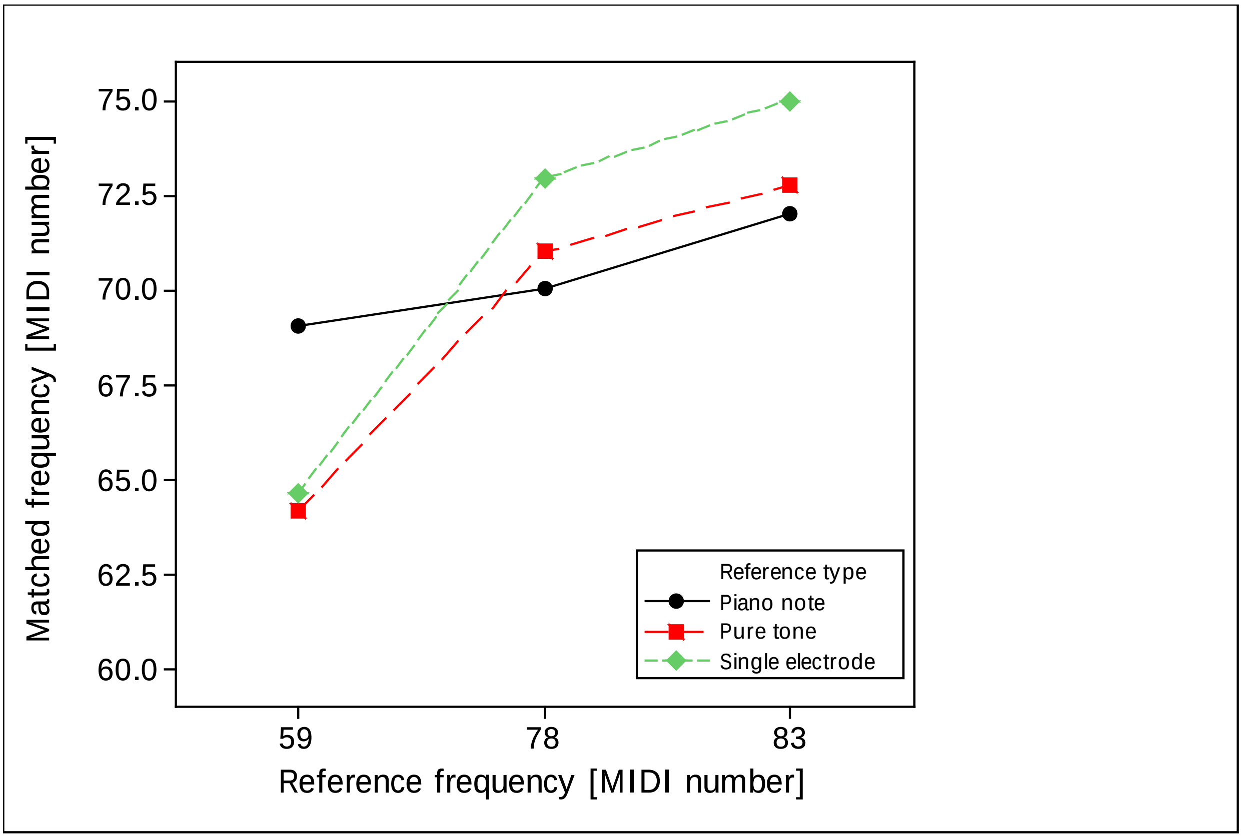

Figure 3-5: the mean of the matched frequency for different Reference Types at low and high frequency, averaged over all Participants, Intensity and Adjustable Type

The horizontal axis shows the MIDI numbers of the Low and High Reference sounds. The matched frequency in MIDI number for the Adjustable sounds is shown on the vertical axis. The mean for the matched frequency depends on the Reference Type.

The statistically significant main effect of Reference Type and the significant interaction of Reference Type with Frequency can be seen in figures 3-4 and 3-5 respectively. The mean pitch matches for the piano notes were higher than for single electrode stimuli and pure tones at the lowest frequency and lower at the higher frequency.

The effect of Adjustable type

The significant main effect of Adjustable Type can be seen in figures 3-4 and 3-6. The mean pitch matches with Adjustable pure tones in Experiments A-1 to C-1 were all higher in frequency than the corresponding pitch matches with Adjustable complex tones in Experiments A-2 to C-2. It should be noted that there was no significant interaction between Reference Type and Adjustable Type. Regardless of the frequency of the Reference sounds, the average matched frequencies were lower for the complex tone Adjustable Type than for the pure tone Adjustable Type as shown in figure 3-6. There was no significant difference in the matched frequency values of MIDI numbers of 78 (750 Hz) and 83 (1000 Hz). The matched frequency selected for low frequency was significantly different from that of both MIDI numbers of 78 and 83 regardless of the type of the adjustable sounds.

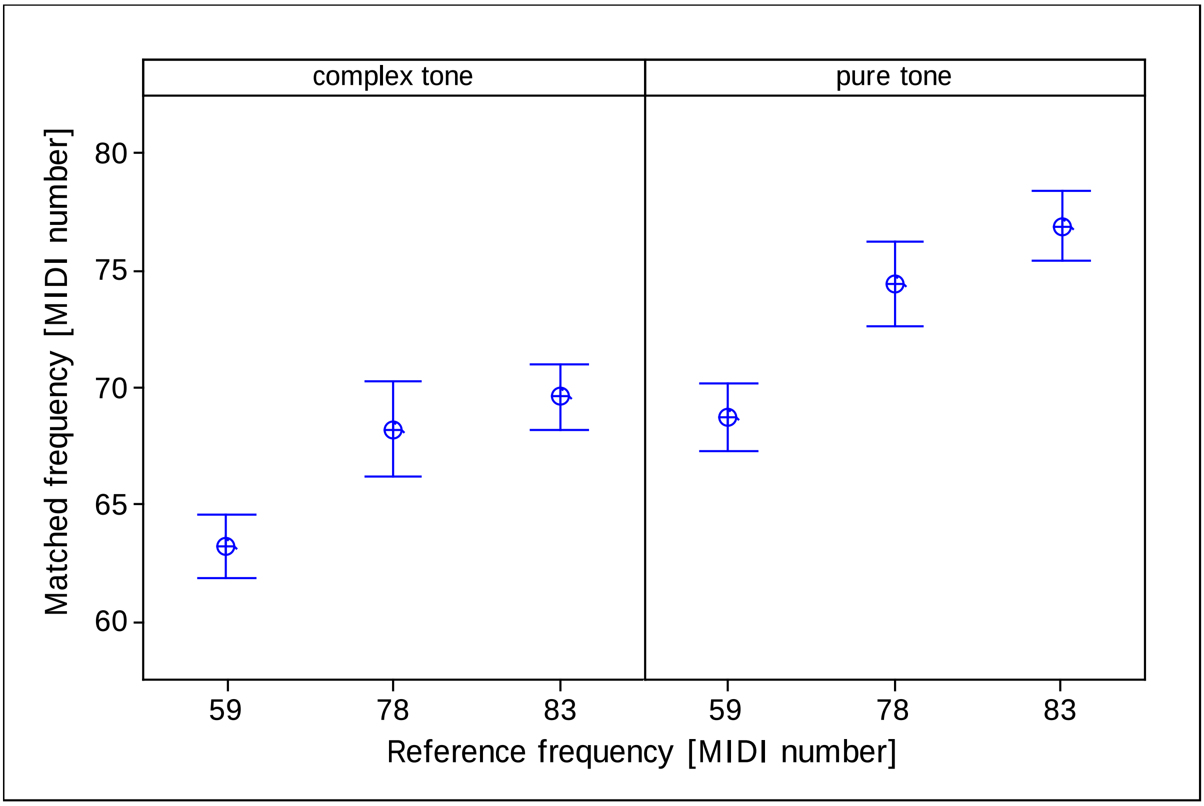

Figure 3-6: 95% confidence intervals of the matched frequency in MIDI numbers for different Adjustable Types, averaged over Reference Type, Intensity and all Participants

Using the Bonferroni procedure for multiple comparisons, there was a significant interaction between Participant and Adjustable Type (df=11, F=3.01, p< 0.001).Although all the participants selected higher matched frequencies for the pure tone Adjustable Type (in experiments A-1, B-1 and C-1) in comparison with the complex tone Adjustable Type (in experiments A-2, B-2 and C-2), this difference ranged from negligible to large, as shown in figure 3-7.

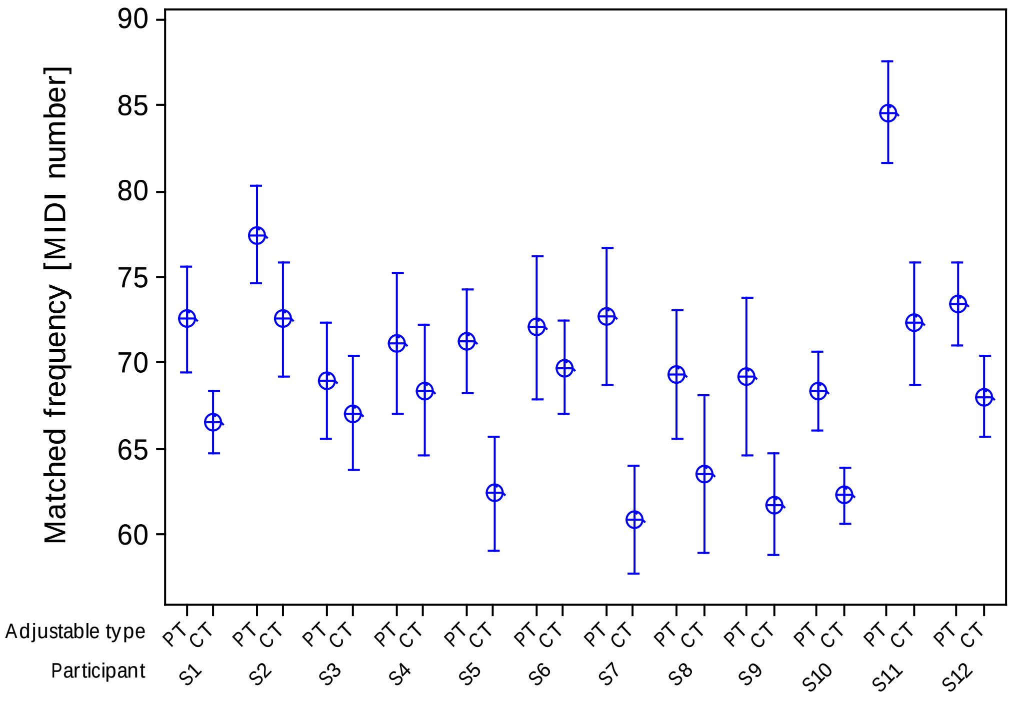

Figure 3-7: the effect of Participant and Adjustable Type, averaged over Intensity, Frequency, and Reference Type

Averaged over Frequency, Reference Type and Adjustable Type, the mean and SD for soft sounds was 70 ± 11.5 MIDI notes (corresponding to a mean of 466 Hz with a range from 254 to 854 Hz) and for loud sounds was 68.8 ±10.3 MIDI notes (corresponding to 434 Hz with a range from 239 to 787 Hz). Figure 3-8 shows the non-significant interaction of Intensity and Adjustable Type. The mean and SD of the perceived pitch for pure tone Adjustable sounds was 73.1 ± 11.8 MIDI notes (corresponding to 557 Hz with a range from 298 to 1102 Hz) at the soft level of intensity and for loud sounds was 72 ± 10 MIDI notes (corresponding to 523 Hz with a range from 293 to 932 Hz). The mean and SD of the perceived pitch for the complex tone Adjustable Type was 66.9 ± 10.3 MIDI notes (390 with a range from 214 to 706 Hz) at soft level of intensity and for loud sound was 65.5 ± 9.5 MIDI notes (359 with a range from 349 to 622 Hz).

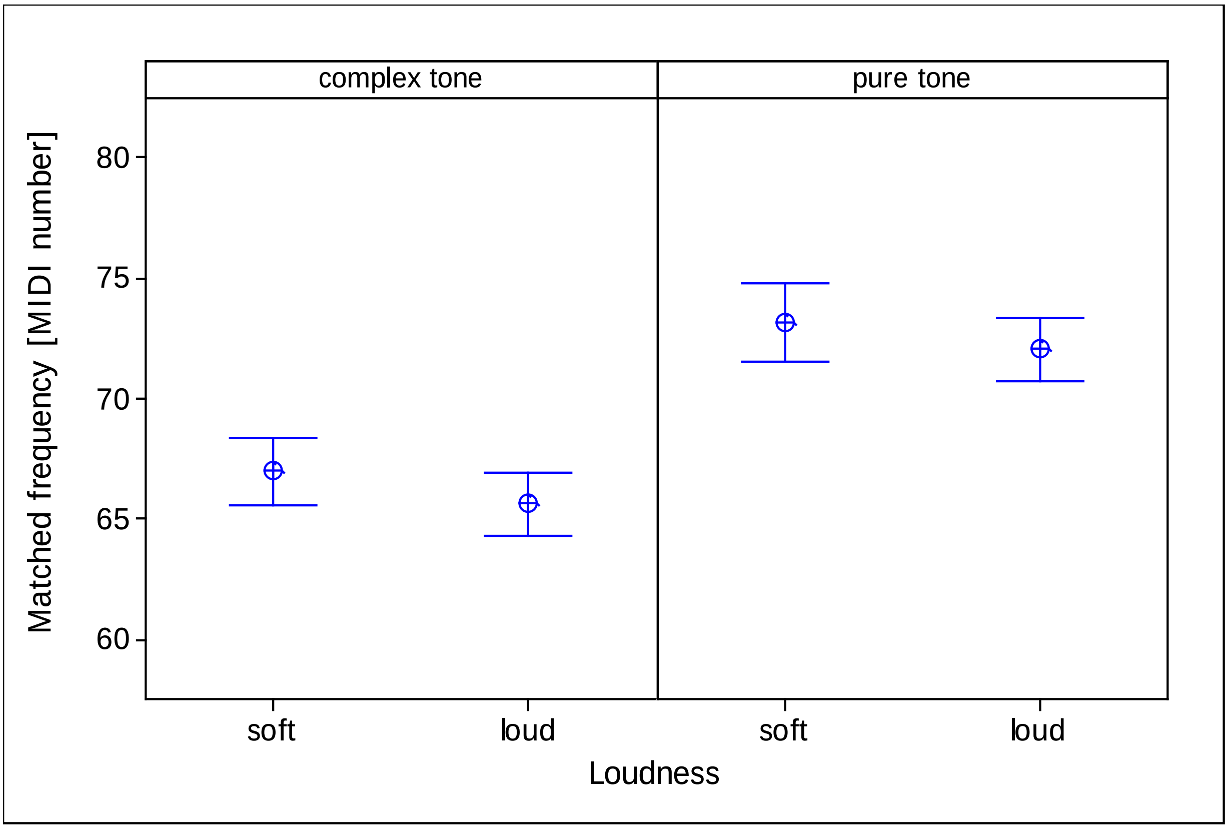

Figure 3-8: the 95% confidence interval for the matched frequency in MIDI number at different levels of Intensity for different Adjustable Types, averaged over Frequency and all Participants

This figure compares the effect of Adjustable Type on the matched frequency selected for soft and loud Reference sounds. The selected matched frequencies when the adjustable sound was a complex tone were lower.

Figure 3-9 shows the non-significant interaction of Reference Type, Frequency and Adjustable Type.

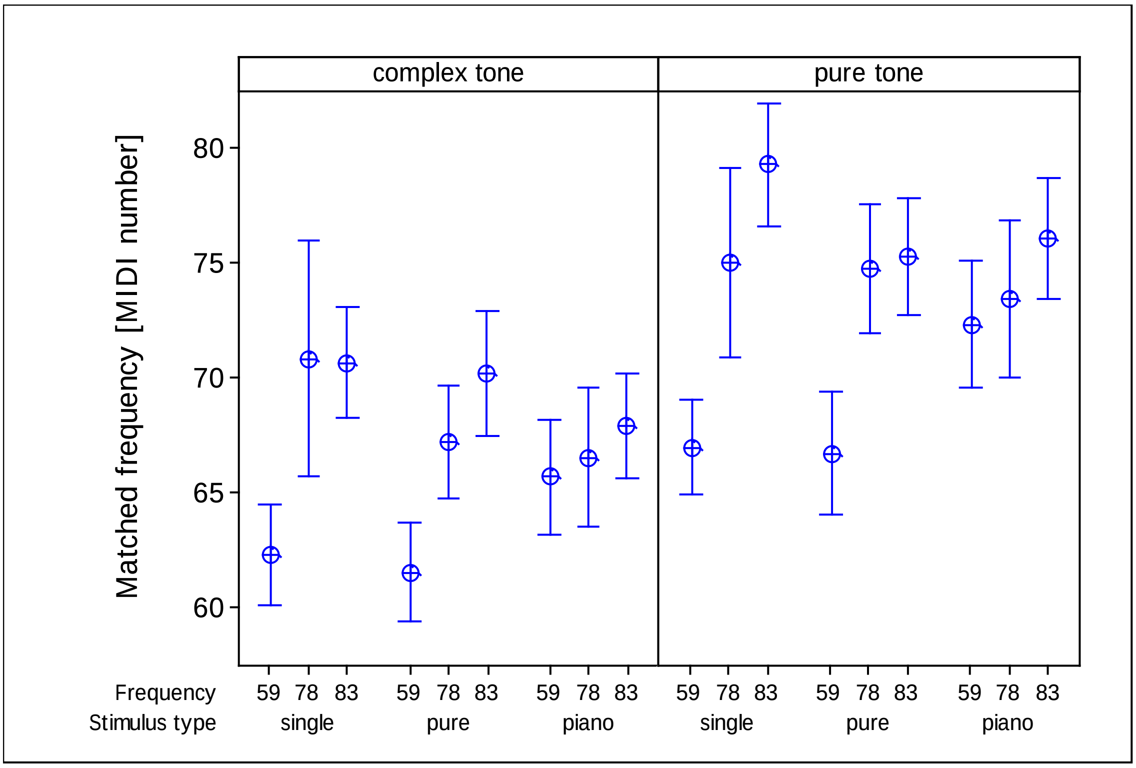

Figure 3-9: the 95% confidence intervals of the matched frequency as a function of Frequency, Reference Type and Adjustable Type, averaged over Intensity and all Participants

This figure compares the effect of Adjustable Type on the matched frequency selected for low (MIDI number of 59) and high (MIDI number of 78 and 83). Generally, the selected matched frequencies were lower when the Adjustable sound was a complex tone.

The effect of Intensity on the matched frequency is of particular interest in this study. Four terms involving Intensity were significant at an α level of 0.05: The main effect of Intensity (p=0.027), the interaction of Intensity with Participant (p=0.021), the interaction of Reference Type and Intensity (p=0.048), and the interaction of Intensity with Participant and Frequency (p=0.018). Figure 3-4 shows that the average matched pitch of loud sounds tended to be slightly lower than that of soft sounds in Experiments A-1, B-1, A-2, and B-2, and loud piano notes were slightly higher in pitch than soft piano notes in Experiments C-1 and C-2.

Individual differences

The interaction between Participant, Frequency and Intensity was not significant after considering Bonferroni correction. Despite this, for some participants, there was a decrease in the perceived pitch for increase in intensity and for other participants, pitch was higher for louder sounds in both low and high frequencies. In other cases, intensity could increase the perceived pitch at one frequency (either low or high) and decrease the perceived pitch at the other frequency (either low or high). These interactions are illustrated below for each experiment separately.

After the consideration of type I error, there was no significant three-way interaction between the Reference Type, Frequency and Participant. Despite this, the participants who performed the experiments showed variability in the matched frequency according to the frequency of the Reference sounds in each experiment. A significant two-way interaction was also observed between the Reference Type and Participant. Figures 3-10 to 3-12 show the effects of Reference Type, Frequency, and Intensity for individual participants, averaged over the other variables.

Figure 3-10 demonstrates that although for most cases on average the lowest matched frequencies were recorded for the pure tone Reference type, for some participants like S2 and S11, the highest matched frequency was selected for the pure tone Reference type. Most cases had higher matched frequency for the piano note condition in comparison with that of the single electrode condition. However, the reverse pattern was observed in some cases (S2, S8 and S12).

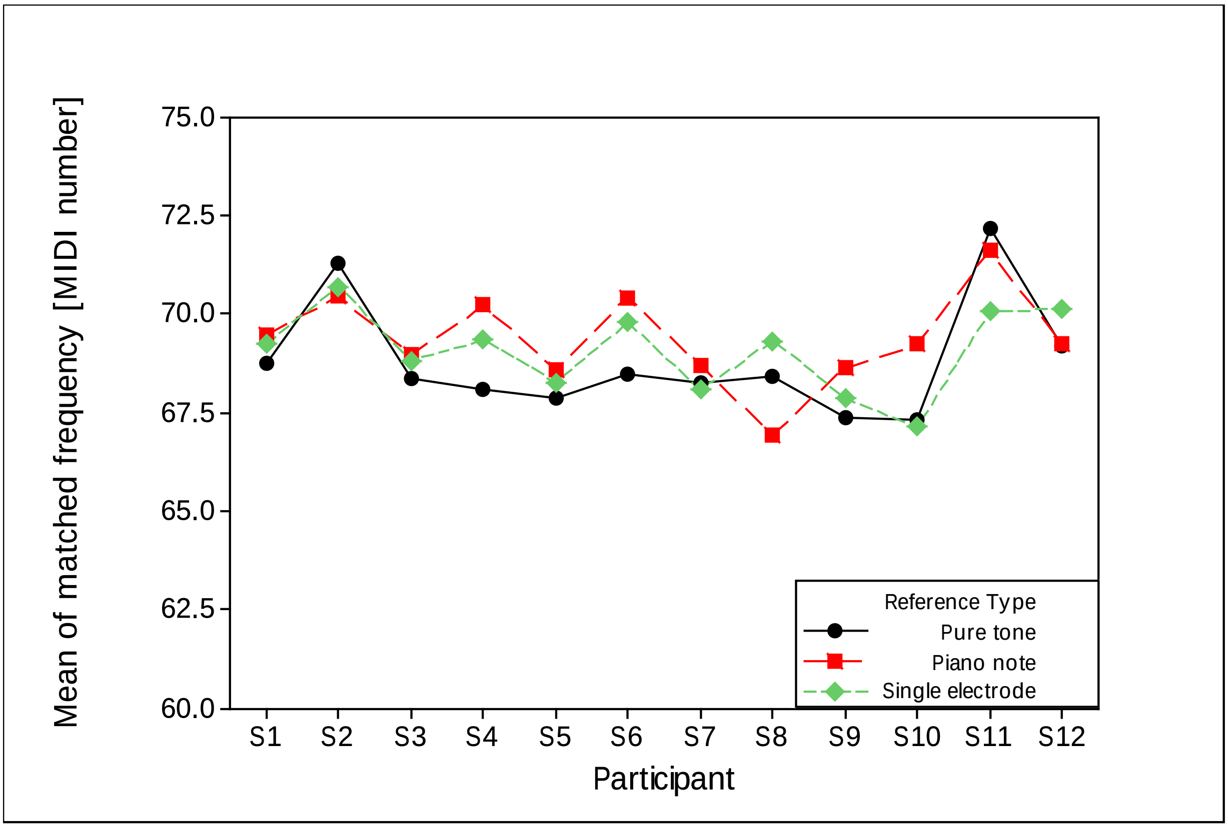

Figure 3-10: the mean of the matched frequency in different experiments for different participants, averaged over Intensity, Frequency and Adjustable Type.

The matched frequency in MIDI number is shown in the vertical axis. The mean for the matched frequency varied from one participant to another. The participants had different means for the matched frequency for different Reference Types.

The interaction observed between Participant and Frequency ($p<0.001$) indicates that people who matched higher frequencies to the high Reference frequency than others did not necessarily have higher matched frequency for the low Reference frequency. This is shown in figure 3-11.

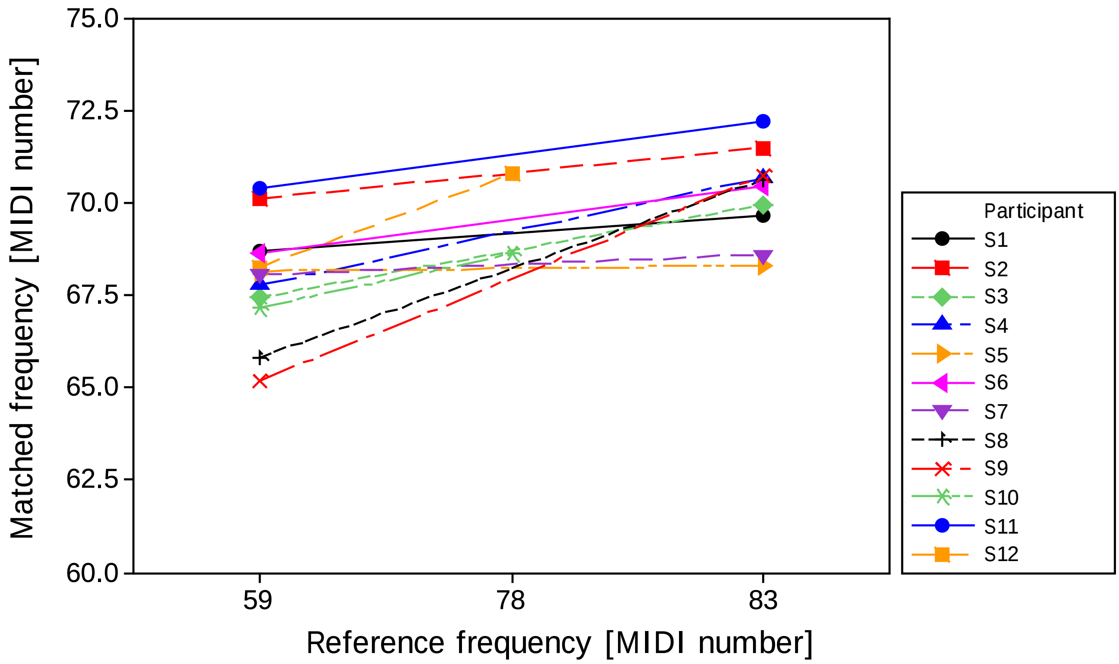

Figure 3-11: the mean of the matched frequency for different participants at low and high reference frequency, averaged over Reference Type, Intensity and Adjustable Type

The horizontal axis shows the MIDI number of the reference sounds. The matched frequency in MIDI number is shown on the vertical axis. The difference in mean for the matched frequency between low and high reference frequency varied from one participant to another.

The effect of Intensity on the matched frequency varied from one participant to another averaged over Reference Type, Frequency, and Adjustable Type. Figure 3-12 shows this interaction (p=0.016). The vertical axis shows the difference of the perceived pitch for the loud Reference sounds from that of the soft sound in semitones. In some cases like S1 and S11, there was a big decrease of about 6 semitones in the perceived pitch with increase in intensity of the Reference sounds while for S3 the perceived pitch increased by about 3 semitones on average when intensity increased.

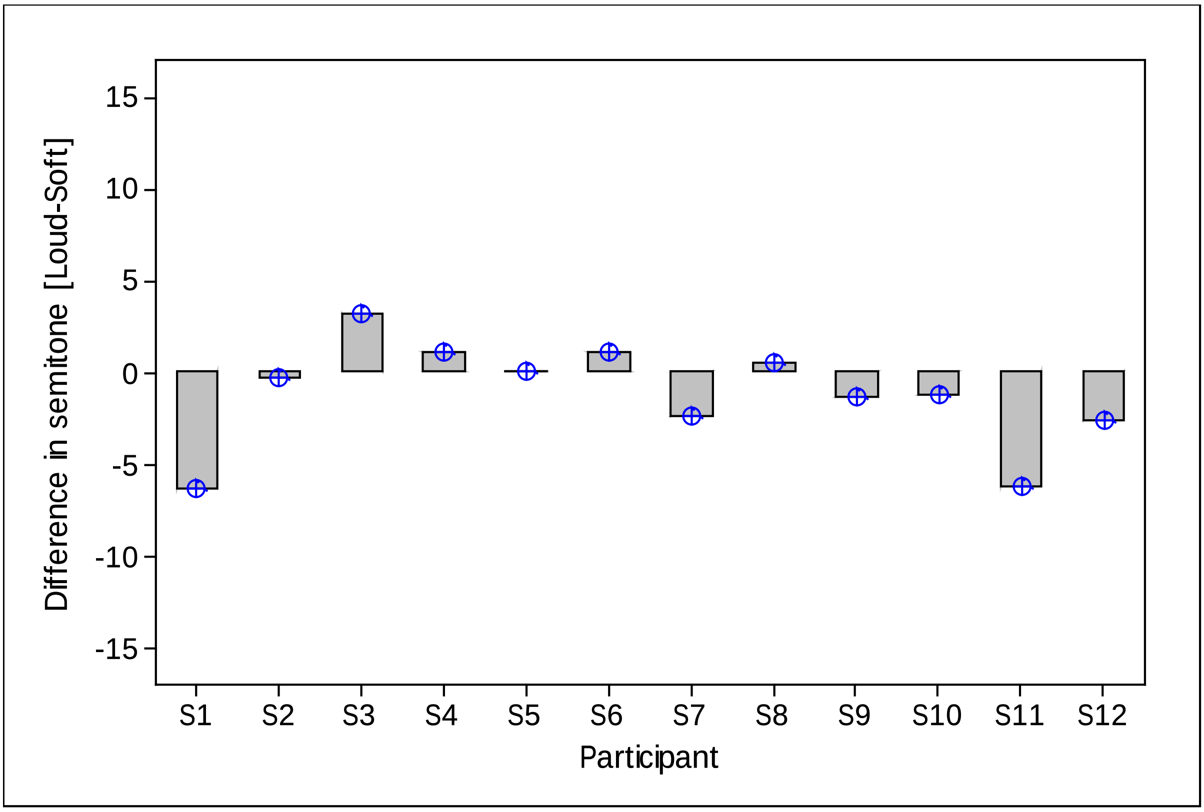

Figure 3-12: the mean change in the matched frequency between soft and loud sounds in semitones for different participants, averaged over Frequency, Reference Type and Adjustable Type.

This figure shows the difference of the matched frequency selected by each participant for loud and soft levels of Intensity in semitones. Negative numbers indicate a decrease in the matched frequency for an increase in Intensity and positive numbers show the increase in the matched frequency at a loud level of Intensity.

Rating of similarity:

Table 3-2 shows that the ratings in different Experiments were significantly different from each other (df=5, F=12.94, $p<0.001$) and that Intensity had a statistically significant effect on ratings (df=1, F=14.36, $p<0.001$). There was no significant difference between the ratings of matches for different Frequencies.

Factor	df	MS	F ratio	P value
Experiment	5	5471.5	12.94	<0.001
Frequency	1	1044.6	2.47	0.116
Intensity	1	6069.6	14.36	<0.001
Experiment*Frequency	5	700.6	1.66	0.142
Experiment*Intensity	5	230	0.54	0.743
Frequency*Intensity	1	392	0.93	0.336
Experiment*Frequency*Intensity	5	366.1	0.87	0.503
Residual	840	422.7		
Total	863			

Table 3-2: ANOVA of the similarity ratings

	Pure tone adjustable sound				Complex tone adjustable sound			
	Low		High		Low		High	
	soft	loud	soft	loud	soft	loud	soft	loud
Single electrode	85.28%	82.28%	83.11%	72.38%	83.44%	72.11%	77.39%	71.38%
Pure tone	84.17%	85.44%	86.11%	77.33%	85.50%	78.39%	78.17%	72.33%
Piano note	69.89%	72.33%	73.89%	68.94%	67.25%	61.17%	71.67%	67.22%

Table 3-3: the mean rating scores for different Experiments for both Adjustable Types at different Frequency and Intensity levels.

As table 3-3 and figure 3-13 show, the mean ratings for piano notes in Experiments C-1 and C-2 were lower than the other Reference Types. The complex tone Adjustable Type in experiments A-2, B-2, and C-2 also resulted in lower similarity ratings than the corresponding experiments A-1, B-1, and C-1 which used the pure tone Adjustable Type. To investigate these differences statistically, a Tukey's post-hoc analysis of Reference is shown in table 3-4. The highest rating score was recorded for the low frequency pure tone Reference when the Adjustable sounds were pure tone. The lowest percentage similarity rating was seen at low frequency piano note Reference sounds when the Adjustable sounds were complex tones.

The number of trials for all participants (N) and the mean rating in each experiment has been shown in table 3-4. The grouping columns in the table show the significant differences among the experiments. If any two experiments do not share at least one similar letter, they will be significantly different. Thus, the mean of rating scores for C-1 was significantly different from A-1, B-1, and B-2. The mean of C-2 was significantly different from A-1, A-2, B-1 and B-2 in the rating task. The difference of means of A-2 and B-1 was also significant.

Grouping Information Using the Tukey Method and 95% Confidence

Experiment	N	Mean	Grouping			
B-1	144	83.2639	A			
A-1	144	80.8611	A	B		
B-2	144	78.5972	A	B		
A-2	144	76.1944		B	C	
C-1	144	71.2639			C	D
C-2	144	66.7917				D

Means that do not share a letter are significantly different.

Table 3-4: post-hoc analysis of the similarity ratings

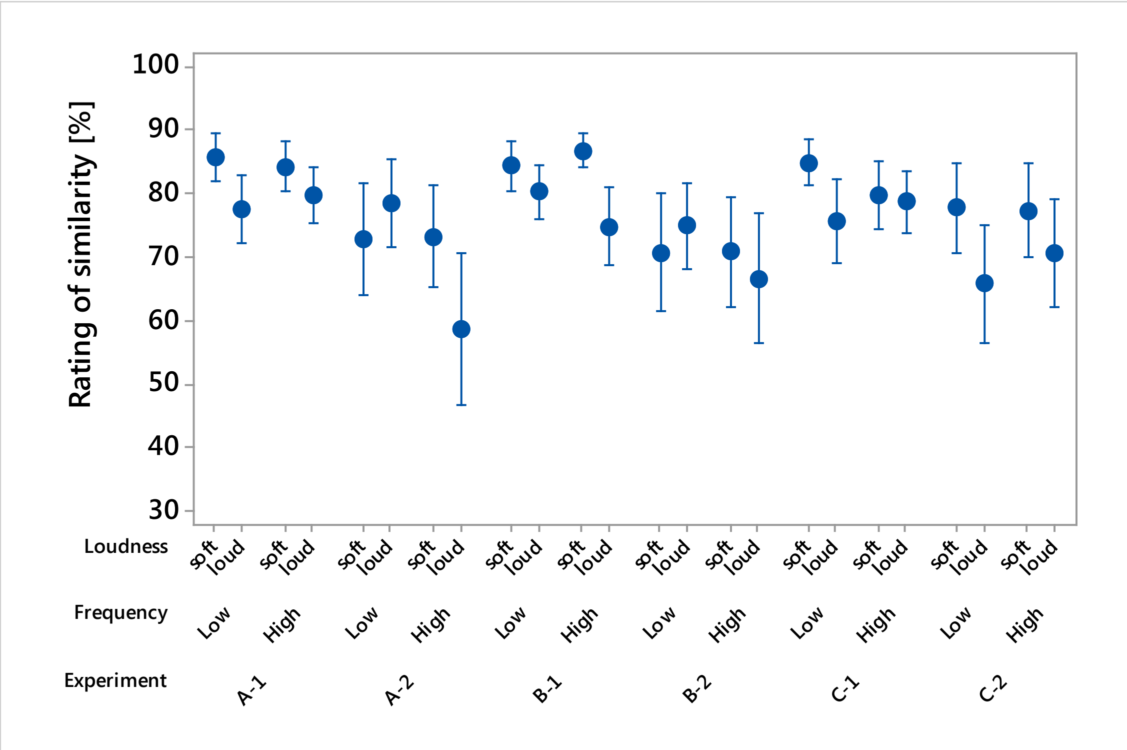

Figure 3-13: the mean rating of similarity for different Frequencies and Intensities of the Reference sounds in different Experiments, averaged over participants

Specific results of experiments A to C

Experiment A-1: Results

Table 3-5 shows the ANOVA result for experiment A-1 in which the single electrode Reference Type was tested, the Adjustable sound was a pure tone and the matched frequency for this condition was recorded.

Factor	df	MS	F ratio	P value
Participant	11	246.21	3.75	<.001
Frequency	1	4823.62	73.49	<.001
Intensity	1	145.52	2.22	0.14
Participant*Frequency	11	106.15	1.62	0.106
Participant*Intensity	11	108.38	1.65	0.097
Frequency*Intensity	1	387.93	5.91	0.017
Participant*Frequency*Intensity	11	70.34	1.07	0.392
Residual	96	65.63		
Total	143			

Table 3-5: ANOVA analysis on the transformed matched frequency of single electrodes (experiment A-1)

The mean and SD of matched frequency for low frequency Reference sounds at the soft level was 66.3 ± 9 MIDI notes (or 376 Hz with a range from 223 to 633 Hz) and at the loud level was 67.6 ± 8.9 MIDI notes (405 Hz with a range from 242 to 678 Hz). The mean and SD of matched frequency for high frequency Reference sounds at the soft level was 81.2 ± 9.6 MIDI notes (890 Hz with a range from 511 to 1549 Hz) and at the loud level was 75.9 ± 9.5 MIDI notes (655 Hz with a range from 378 to 1128 Hz).

The participants performed differently from one another in this experiment, but there was no significant interaction with the other factors. The frequency of the Reference sounds influenced the matched frequency and the effect was dependent on the intensity of the Reference sounds. The intensity of the Reference sounds did not reach statistical significance by itself.

An important finding of this experiment was the variability among the participants. As figure 3-14 clearly demonstrates for some people, the change in the perceived pitch with intensity was quite large. The Y axis of the figure shows the difference of perceived pitches at loud and soft sounds [i.e. perceived pitch at loud minus perceived pitch at soft]. Negative numbers and positive numbers indicate decreases and increases in the matched frequency with increasing intensity respectively. This figure shows the difference of the matched frequency selected by each participant for loud and soft levels of intensity in semitones at low (yellow) and high (green) frequencies. Differences in both directions (increases and decreases) were observed. There were large effects of intensity on the matched frequency for S1, S6, S7, S8, and S11. In S1 and S7, the direction of change was negative for both low and high frequencies while for S6, S8, S10 and S11, decreases in the matched frequency happened at high frequencies while at low frequencies, an increase in the matched frequency was observed. For some people like S3 and S9, a noticeable change occurred in just one of the low or high frequencies without a significant change in the other frequency.

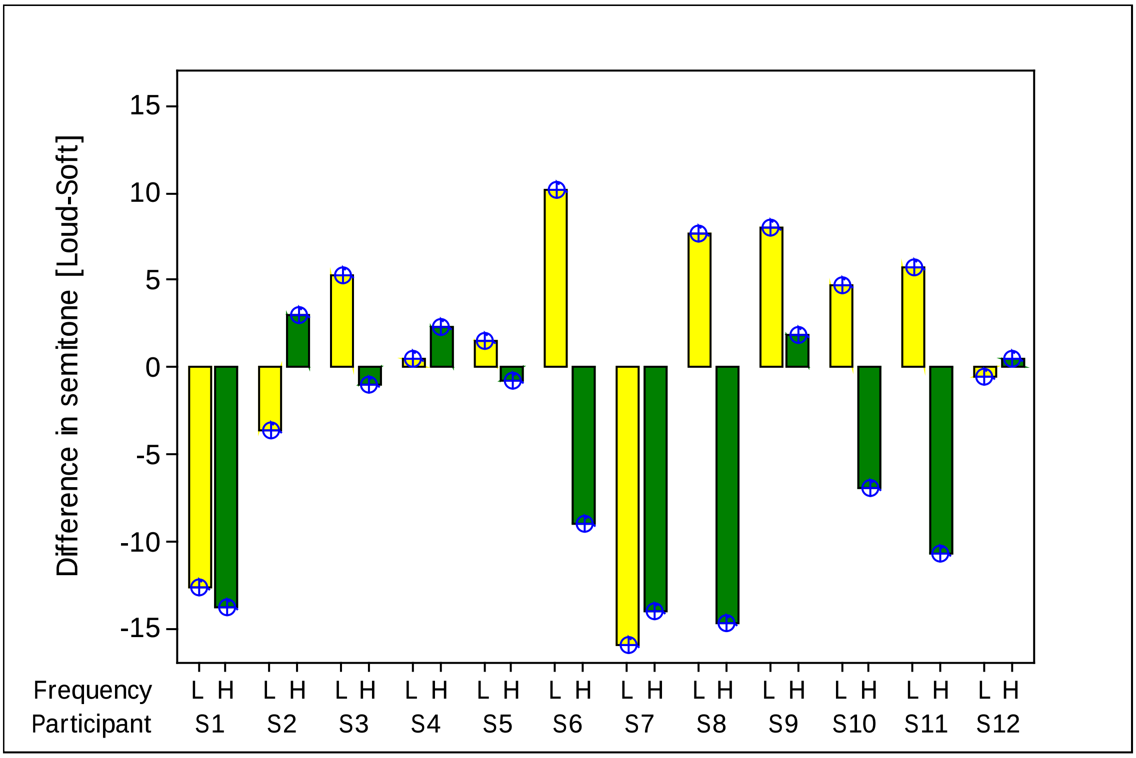

Figure 3-14: the mean difference in the matched frequency between loud and soft sounds in semitones for different participants at low and high frequencies in experiment A-1

Experiment A-2: Results

Table 3-8 shows the ANOVA analysis for the single electrode Reference Type and the complex tone Adjustable Type in Experiment A-2. The effect of Intensity on the matched frequency was significant (df=1, F=4.66 and p=0.033). Other factors which were influential in pitch matching were the Frequency of the Reference sounds and the

Participant who was matching the Adjustable sounds in non-implanted ear to the Reference sound in the implanted ear.

Factor	df	MS	F ratio	P value
Participant	11	314.08	5.07	<.001
Frequency	1	2536.22	40.96	<.001
Intensity	1	288.59	4.66	0.033
Participant*Frequency	11	127.73	2.06	0.03
Participant*Intensity	11	42.85	0.69	0.743
Frequency*Intensity	1	19.73	0.32	0.574
Participant*Frequency*Intensity	11	47.95	0.77	0.665
Residual	96	61.92		
Total	143			

Table 3-6: ANOVA analysis on the matched frequency of single electrode condition (experiment A-2)

The mean and SD of matched frequency for low frequency Reference sounds at the soft level was 64 ± 8.7 MIDI notes (329 Hz with range from 216 to 544 Hz) and at the loud level was 60.5 ± 9.7 MIDI notes (269 Hz with range from 152 to 417 Hz). The mean and SD of matched frequency for high frequency Reference sounds at the soft level was 71.7 ± 9.2 MIDI notes (514 Hz with range from 302 to 825 Hz) and at the loud level was 69.6 ± 8.9 MIDI notes (455 Hz with range from 270 to 761 Hz).

Figure 3-15 shows the mean change in the matched frequency with increase in Intensity in semitones for Experiment A-2. The Y axis of the figure shows the difference of perceived pitches at loud and soft sounds [i.e. perceived pitch at loud minus perceived pitch at soft]. Negative numbers and positive numbers indicate decreases and increases in the matched frequency with increasing intensity respectively. This difference of the matched frequency in semitones was shown at low (yellow) and high (green) frequencies. In cases S1, S5, S6 and S7 the change in the perceived pitch at both low and high frequencies happened in the same direction while for some others the direction of changes depended on the frequency of the Reference sounds (S2, S3, S4 and S8). In some of the participants there was a big change in the perceived pitch in one frequency with small if any change for the other frequency (S9, S10, S11 and S12).

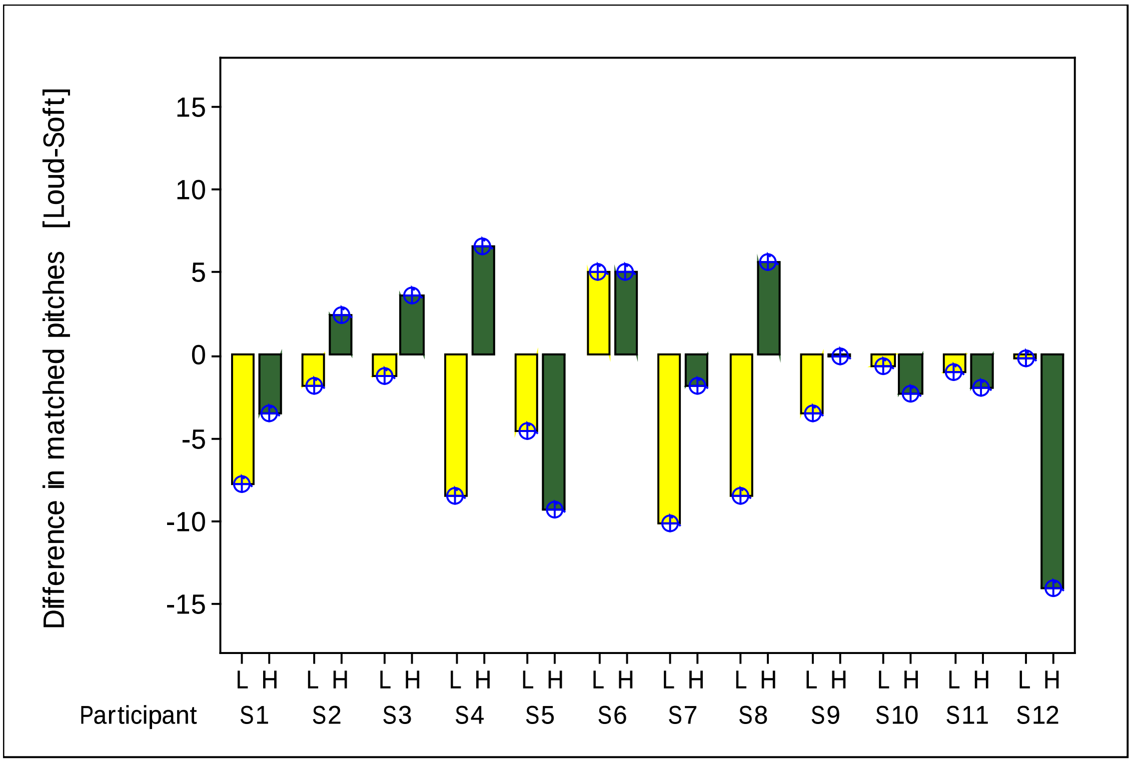

Figure 3-15: the mean difference in the matched frequency between loud and soft sounds in semitones for different participants at low and high frequencies in Experiment A-2

This figure shows the difference of the matched frequency selected by each participant for loud and soft levels of Intensity in semitones at low (yellow) and high (green) frequencies. Negative numbers indicate decrease in the matched frequency for increase in Intensity and positive numbers show increase in the matched frequency at the loud level.

Experiment B-1: Results

Table 3-6 summarises the ANOVA for Experiment B-1 in which the pure tone Reference Type was tested and the Adjustable Type was also a pure tone. The matched frequency was determined by the frequency of the Reference (df=1, F=39.38, p <.001) although it was also dependent on the participant who was matching the two sounds. The intensity of the pure tone Reference sounds did not affect the perceived pitch on average (df=1, F= 1.38, p =0.243).

Factor	df	MS	F ratio	P value
Participant	11	417.95	6.47	<.001
Frequency	1	2572.26	39.83	<.001
Intensity	1	89.12	1.38	0.243
Participant*Frequency	11	243.35	3.77	<.001
Participant*Intensity	11	77.66	1.2	0.296
Frequency*Intensity	1	26	0.4	0.527
Participant*Frequency*Intensity	11	52.2	0.81	0.632
Residual	96	64.58		
Total	143			

Table 3-7: ANOVA of the matched frequency of pure tones (experiment B-1)

The mean and SD of matched frequency for low frequency Reference sounds at the soft level was 67.9 ± 12 MIDI notes (412 Hz with a range from 206 to 825 Hz) and at the loud level was 65.5 ± 10.2 MIDI notes (359 Hz with a range from 204 to 647 Hz). The mean and SD of matched frequency for high frequency Reference sounds at the soft level was 75.5 ± 10.5 MIDI notes (640 Hz with a range from 349 to 117 Hz) and at the loud level was 74.8 ± 7.9 MIDI notes (615 Hz with a range from 389 to 970 Hz).

Figure 3-16 shows the change in the perceived pitch with Intensity. The Y axis of the figure shows the difference of perceived pitches at loud and soft sounds [i.e. perceived pitch at loud minus perceived pitch at soft]. Negative numbers and positive numbers indicate decreases and increases in the matched frequency with increasing intensity respectively. This figure shows the difference of the matched frequency selected by each participant for loud and soft levels of intensity in semitones at low (yellow) and high (green) frequencies. Like experiment A-1 and A-2, when the intensity of the Reference sound increased, in some cases the difference between perceived pitch of soft and loud sounds was large and in some cases was quite negligible. The large changes for some people were in the same direction for high and low frequency Reference tones (either both decreased or increased) and in other cases the changes were in opposite directions. Another finding from the figure was that the pattern of decrease or increase in the perceived pitch was not similar to that in experiment A-1 or A-2. People with larger changes in the perceived pitch in this experiment were not the same people with large changes in experiment A-1 or A-2. There were some large changes of the matched frequency with intensity in the same direction at both high and low frequency for S3 and S11. For S2 and S5, the substantial effects were observed in either low or high frequencies only.

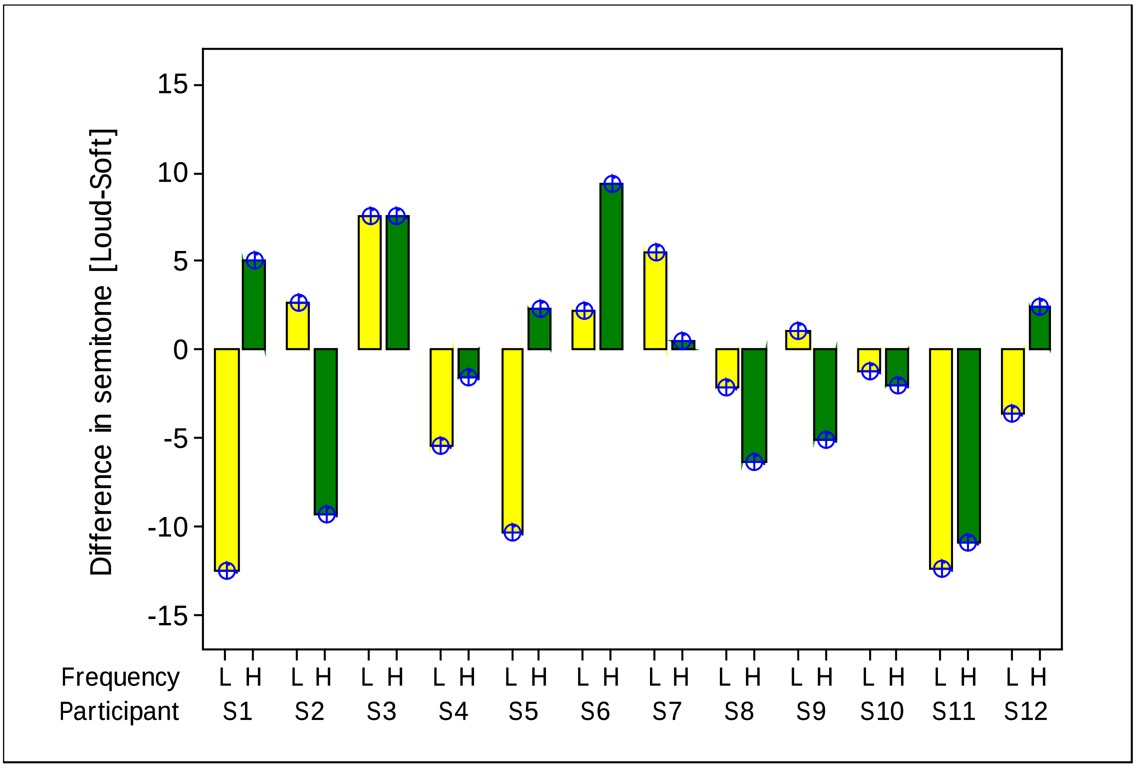

Figure 3-16: the mean difference in the matched frequency between loud and soft sounds in semitones for different participants at low and high frequencies in experiment B-1

This figure shows the difference of the matched frequency selected by each participant for loud and soft levels of Intensity in semitones at low (yellow) and high (green) frequencies. Negative numbers indicate a decrease in the matched frequency for increases in intensity, and positive numbers show an increase in the matched frequencies at loud intensity.

Experiment B-2: Results

In experiment B-2, the effect of intensity on the perceived pitch of a pure tone Reference was assessed when it was matched by an Adjustable complex tone. Table 3-8 summarises the statistical analysis for this experiment.

Factor	df	MS	F ratio	P value
Participant	11	266.27	5.8	<.001
Frequency	1	2386.6	51.95	<.001
Intensity	1	217.92	4.74	0.032
Participant*Frequency	11	328.52	7.15	<.001
Participant*Intensity	11	35.25	0.77	0.671
Frequency*Intensity	1	3.2	0.07	0.792
Participant*Frequency*Intensity	11	120.99	2.63	0.006
Residual	96	45.94		
Total	143			

Table 3-8: ANOVA analysis on the matched frequency data in experiment B-2

The matched frequency in this experiment was determined by a combination of all factors. The different performances of different participants varied also at different frequencies and intensities of the Reference sounds as shown by the significant interaction of Participant, Frequency and Intensity).

The mean and SD of matched frequency for low frequency Reference sounds at the soft level was 62.9 ± 10.4 MIDI notes (309 Hz with range from 169 to 564 Hz) and at the loud level was 60.1 ± 7.8 MIDI notes (263 Hz with range from 167 to 412 Hz). The mean and SD of matched frequency for high frequency Reference sounds at the soft level was 70.7 ± 11.5 MIDI notes (485 Hz with range from 249 to 943 Hz) and at the loud level was 68.6 ± 7.5 MIDI notes (429 Hz with range from 273 to 663 Hz).

Figure 3-17 shows change in the perceived pitches of different participants. The Y axis of the figure shows the difference of perceived pitches at loud and soft sounds [i.e. perceived pitch at loud minus perceived pitch at soft]. Negative numbers and positive numbers indicate decreases and increases in the matched frequency with increasing intensity respectively. This figure shows the difference of the matched frequency selected by each participant for loud and soft levels of intensity in semitones at low (yellow) and high (green) frequencies. As in the other Experiments, in some cases (S5, S8 and S12) the changes in the perceived pitch were big and in some cases were negligible (S6, S9 and S10). Some people showed different pitch with intensity for both single electrode and pure tone Reference Types while some just showed a big change in one of these Reference Types (Comparison between figures 3-15 and 3-17). Yellow bars in the figure show the difference of the matched frequency selected by each participant for loud and soft levels of intensity in semitones at low frequency and green bars for high frequencies.

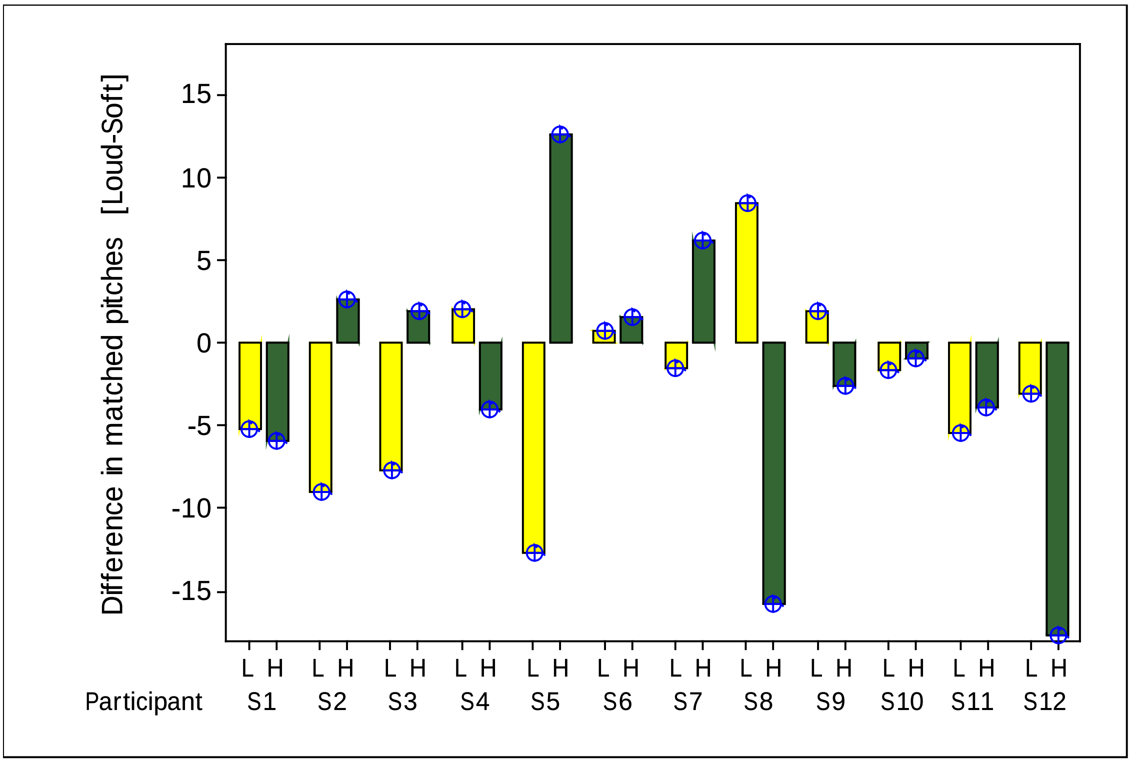

Figure 3-17: the mean difference in the matched frequency between loud and soft sounds in semitones for different participants at low and high frequencies in Experiment B-2

Experiment C-1: Results

Table 3-9 summarises the ANOVA for Experiment C-1 in which the piano note Reference Type was matched with a pure tone Adjustable Type. In this experiment, the intensity of the complex tone Reference sounds did not change the perceived pitch significantly and the main factor which determined the matched frequency was the Frequency of the

Reference sounds (df=1, F=4.17, p =0.044). In addition, the matched frequency was also influenced by Participant. These significant effects for piano notes were weaker than for pure tones or single electrodes in Experiments A-1 and B-1.

Factor	df	MS	F ratio	P value
Participant	11	271.25	2.89	0.003
Frequency	1	390.97	4.17	0.044
Intensity	1	1.69	0.02	0.894
Participant*Frequency	11	104.79	1.12	0.356
Participant*Intensity	11	120.15	1.28	0.247
Frequency*Intensity	1	59.68	0.64	0.427
Participant*Frequency*Intensity	11	130.7	1.39	0.188
Residual	96	93.77		
Total	143			

Table 3-9: ANOVA of the matched frequency for experiment C-1

The mean and SD of matched frequency for low frequency Reference sounds at the soft level was 72.8 ± 12.6 MIDI notes (543 Hz with a range from 264 to 1134 Hz) and at the loud level was 71.7 ± 10.7 MIDI notes (514 Hz with a range from 277 to 954 Hz). The mean and SD of matched frequency for high frequency Reference sounds at the soft level was 74.8 ± 10.8 MIDI notes (615 Hz with a range from 329 to 1147 Hz) and at the loud level was 76.3 ± 7.8 MIDI notes (670 Hz with a range from 427 to 1052 Hz).

One finding in experiment C-1 (piano notes) was large changes in the matched frequency with intensity which occurred in opposite directions (S4, S7, S8 and S9 and S11). In these cases the change in the perceived pitch in one of two frequencies was quite substantial (figure 3-18). The Y axis of the figure shows the difference of perceived pitches at loud and soft sounds [i.e. perceived pitch at loud minus perceived pitch at soft]. Negative numbers and positive numbers indicate decreases and increases in the matched frequency with increasing intensity respectively. This figure shows the difference of the matched frequency selected by each participant for loud and soft levels of intensity in semitones at low (yellow) and high (green) frequencies. Large changes in the same direction for both low and high frequencies were observed in some cases (S1, S2 and S3). For S3, increased intensity increased the perceived pitch for both low and high frequencies while for S1 and S2, a decrease in perceived pitch was observed. For S5, a substantial change in the matched frequency took place at high frequencies with no change at low frequencies.

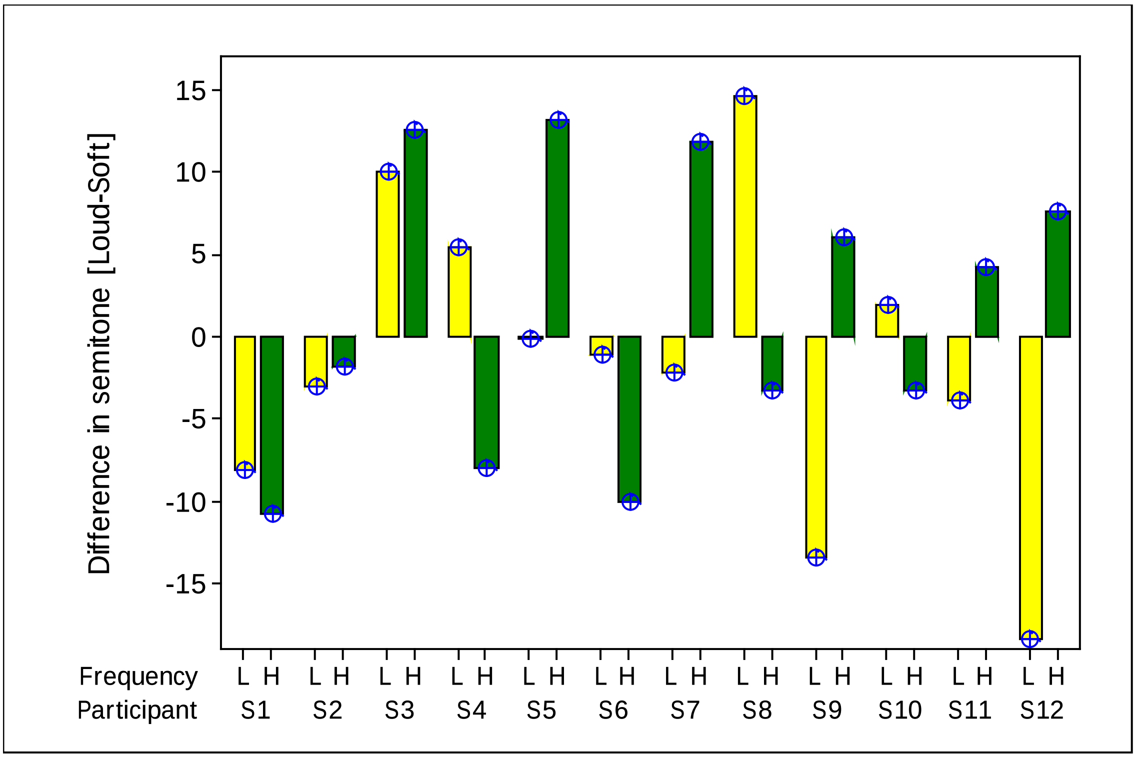

Figure 3-18: the mean difference in the matched frequency between loud and soft piano notes in semitones for different participants at low and high frequencies in experiment C-1

This figure shows the difference of the matched frequency selected by each participant for loud and soft levels of intensity in semitones at low (yellow) and high (green) frequencies. Negative numbers indicate a decrease in the matched frequency for increase in intensity and positive numbers show an increase in the matched frequency at loud intensity.

Experiment C-2: Results

In this experiment, piano notes were the Reference sounds and the Adjustable sound was complex sounds presented to the non-implanted ear. Table 3-10 is the output of the ANOVA analysis for this experiment.

Factor	df	MS	F ratio	P value
Participant	11	174.38	2.22	0.019
Frequency	1	138.98	1.77	0.187
Intensity	1	51.48	0.66	0.42
Participant*Frequency	11	106.74	1.36	0.205
Participant*Intensity	11	113.87	1.45	0.164
Frequency*Intensity	1	1.56	0.02	0.888
Participant*Frequency*Intensity	11	74.57	0.95	0.498
Residual	96	78.56		
Total	143			

Table 3-10: ANOVA analysis on the matched frequency of piano notes in Experiment C-2

As table 3-10 shows, neither the Intensity nor Frequency of the Reference sounds was a determining factor for the matched frequency. However, Participant had a significant effect.

The mean and SD of matched frequency for low frequency Reference sounds at the soft level was 65.2 ± 11.2 MIDI notes (353 Hz with a range from 185 to 674 Hz) and at the loud level was 66.1 ± 10 MIDI notes (372 Hz with a range from 208 to 663 Hz). The mean and SD of matched frequency for high frequency Reference sounds at the soft level was 66.9 ± 7.7 MIDI notes (389 Hz with a range from 252 to 608 Hz) and at the loud level was 68.3 ± 8.7 MIDI notes (422 Hz with a range from 255 to 698 Hz).

Figure 3-19 shows the variability among people in pitch matching with increase in Intensity for the piano note Reference Type and complex tone Adjustable Type. The Y axis of the figure shows the difference of perceived pitches at loud and soft sounds [i.e. perceived pitch at loud minus perceived pitch at soft]. Negative numbers and positive numbers indicate decreases and increases in the matched frequency with increasing intensity respectively. This figure shows the difference of the matched frequency selected by each participant for loud and soft levels of intensity in semitones at low (yellow) and high (green) frequencies

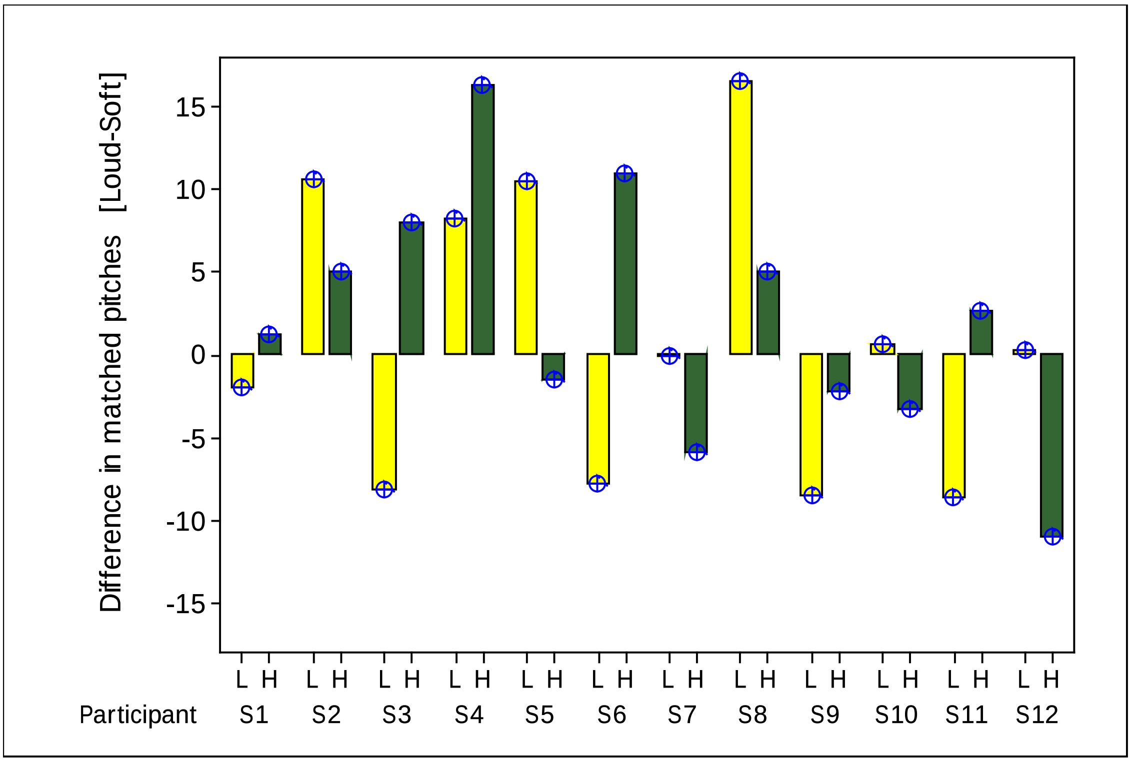

Figure 3-19: the mean difference in the matched frequency between loud and soft sounds in semitones for different participants at low and high frequencies in experiment C-2

This figure shows the difference of the matched frequency selected by each participant for loud and soft levels of intensity in semitone at low (yellow) and high (green) frequencies. Negative numbers indicate a decrease in the matched frequency for increase in intensity and positive numbers show an increase in the matched frequency at loud levels of intensity.

Discussion

The main hypothesis of the thesis was that "The intensity and quality of sound would affect the pitch of sounds perceived by cochlear implant users." This hypothesis is supported by the results as shown by the significant effects of Intensity and Reference Type in Table 3-1, and the role that these two factors play in several other statistically significant interactions. The main effects of Reference Type and Intensity are clearly shown in figure 3-4.

The other factors that were varied in the experiments (Frequency, Adjustable Type, and Participant) also significantly affected the results, and the effects of all factors are discussed below. Each experiment was designed to assess specific hypotheses. The first hypothesis of all experiments was about the perceived pitch in the experiments in relation to Greenwood's function. The second hypothesis of all experiments was about the effect of intensity on the perceived pitch at low and high frequencies. The third hypothesis was about the similarity rating of both sounds at matching point. Each of these hypotheses is discussed in following sections.

Perceived pitch and Greenwood's function

For experiments A-1 and B-1, Hypothesis 1 was that the pitch matches would be in accord with the Greenwood function and for experiment C-1, that the pitch matches for piano notes at the low frequency would be higher than for the corresponding pure tones and single electrodes. For convenience, Figure 3-20 shows the mean pitch matches for soft and loud Intensities and low and high Frequencies in experiments A-1 to C-1 superimposed on the range of pitches expected from the Greenwood function. Figure 3-21 shows the corresponding data for the individual participants, averaged over loud and soft levels of intensity.

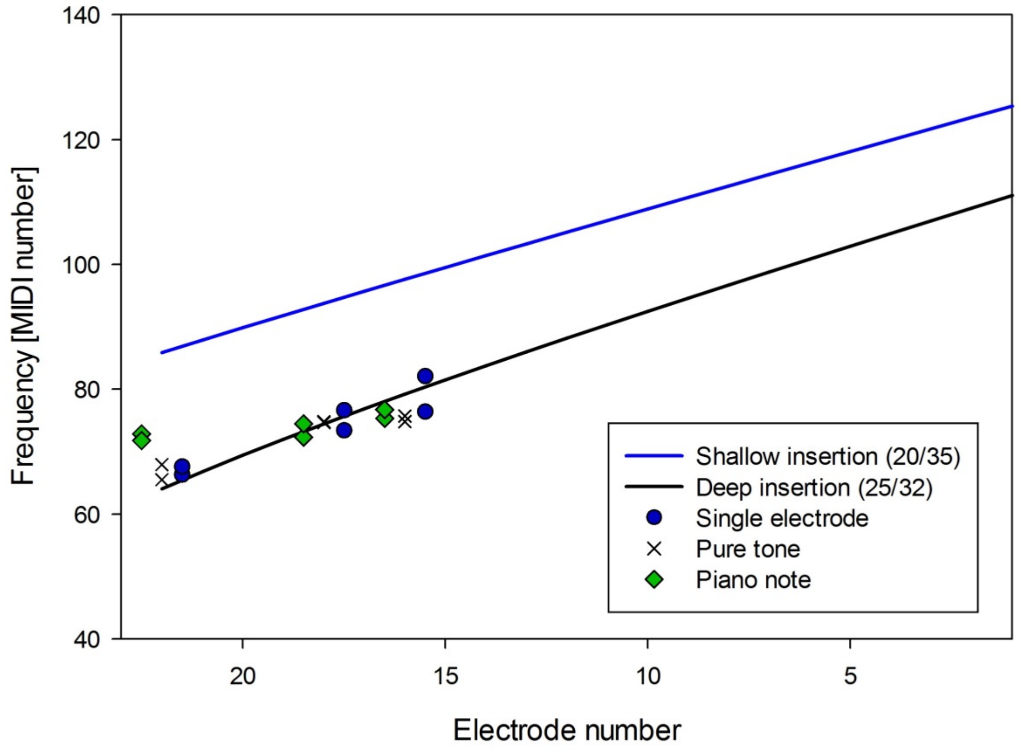

Figure 3-20: the mean of the matched frequency for experiments A-1, B-1 and C-1 in relation to the range which is expected from Greenwood's function. The blue line (upper line) shows the highest estimation of the stimulated electrodes when there is a cochlea with 35 mm length and a short insertion depth of 20 mm. The black line indicates the lowest pitch estimation based on Greenwood's function provided that there is deep insertion of the electrode array within a short cochlea.

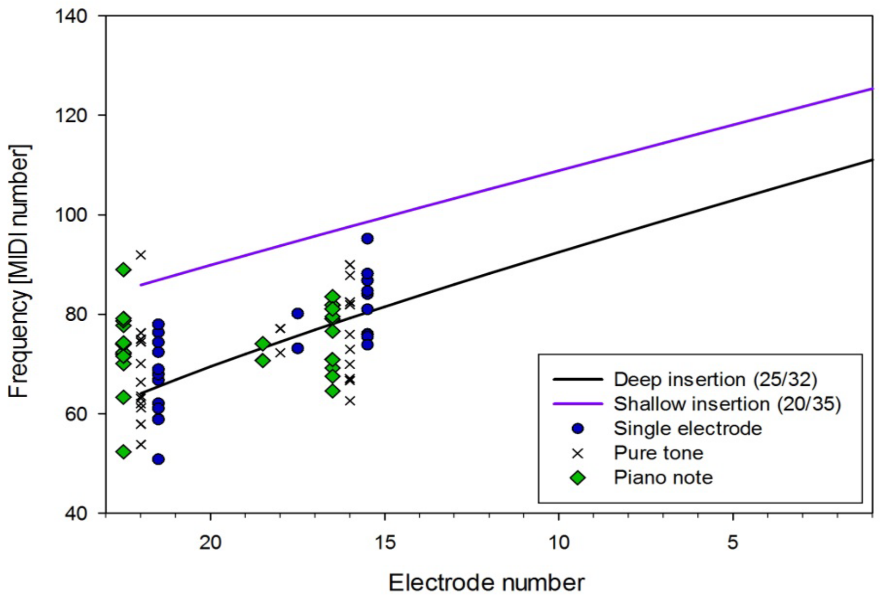

Figure 3-21: the mean matched frequency for each participant in Experiments A-1 to C-1 in relation to the range which is expected from Greenwood's function.

The mean data for the low frequency supports hypothesis 1 for each experiment A-1, B-1 and C-1, the mean of the matched frequencies selected for low frequency were 376 Hz at the soft level (66.4 in MIDI number) and 405 Hz at the loud level (67.6 in MIDI number) for the single electrode experiment (A-1). The mean matched frequencies in experiment B-1 were not significantly different from those in experiment A-1. As figure 3-20 shows, they are very close to the lowest estimation of Greenwood's equation. While Carlyon, Macherey et al. (2010b) proposed 900-1000 Hz for the mean of the most apical electrode, the present finding was consistent with most studies which reported 150-400 Hz as the mean matches for the most apical electrode (Blamey, Dooley et al. 1996, Baumann and Nobbe 2006, Dorman, Spahr et al. 2007, McDermott, Sucher et al. 2009, Green, Faulkner et al. 2012). In the above-mentioned studies, the insertion depth or angle of the most apical electrode was calculated and the matched frequency was compared to Greenwood's equation. The perceived pitch was significantly lower than the predicted pitch. These studies concluded that Greenwood's equation is not reliable in estimation of the perceived pitch of the most apical electrode. Blamey, Dooley, et al (1996) postulated that pitch was perceived as being lower than expected because the spiral ganglion cell dendrites that were originally connected to hair cells retracted back to the cell soma in Rosenthal's Canal after the hair cells died away. In the apical region of the cochlea, the soma are displaced in the basal direction from the hair cells and therefore soma with low characteristic frequency are stimulated by electrodes that are located more basally than predicted by Greenwood's function.

Figure 3-21 indicates that many of the pitch matches for individual participants fell below the expected range at both low and high frequencies. These observations are consistent with previous findings that the perceived pitches for the most apical electrode are lower than predicted for most cochleae and electrode arrays (Blamey, Dooley et al. 1996, Baumann and Nobbe 2006, Boëx, Baud et al. 2006, Dorman, Spahr et al. 2007). Only if the length of the cochlea was short, the insertion of the electrode was deep and there was an ideal electrode-neuron interface, would the perceived pitch be consistent with Greenwood's function. There are many reasons that such perfect conditions are not met for most CI users.

The perceived pitch of the low frequency piano note in experiment C-1 was significantly higher than that of single electrode and pure tone Reference Types in experiments A-1 and B-1 as predicted by hypothesis C.

The range of the mean selected matched frequency for the Reference frequency of 750 Hz (or 78 in MIDI number) was from 72.4 to 76.7, which are between about 1 to 6 semitones lower than the perfect match. The mean of the matched frequency for 1000 Hz (with MIDI number of 83) varied from 74.8 to 82.1, which are about 1 to 8 semitones lower than the perfect match.

Another common trend in results among these three experiments was that while the perceived pitch for low frequency was higher than the perfect match, the perceived pitch for high frequency was lower than the perfect match. The slope of the pitch match frequency versus electrode data is similar to the slope of the Greenwood function. This means that there is a compression of the perceived pitch range by a factor of 1.5 to 3 in the implanted ear (16 semitones from 66 to 82 MIDI notes at the soft level and 8 semitones from 68 to 76 at the loud level for the single electrode), compared with the non-implanted ear (24 semitones from 59 to 83 MIDI notes).

In experiments A-2 to C-2, the mean of the matched frequencies for the low frequency stimuli were between 1.5 to 6 semitones above the perfect match of MIDI note 59. The difference was greatest in the piano note experiment (C-2). The matched frequencies for high frequency stimuli (either electrode number 18 or 16) were below the perfect pitch matches. A range of difference from 11 to 16 semitones was perceived between the perceived pitch and the perfect match at high frequency. It is worth mentioning that people with hearing loss in the non-implanted ear often have less than perfect pitch perception as well. This may contribute to the observed differences in semitones in comparison with the estimation of Greenwood's function.

Figure 3-22 shows that the perceived pitches for nearly all levels and frequencies in experiments A-2 to C-2 were lower than expected from Greenwood's function. Only the matched frequencies for the lowest frequency in the piano note experiment (C-2) were close to the lowest prediction of Greenwood's function.

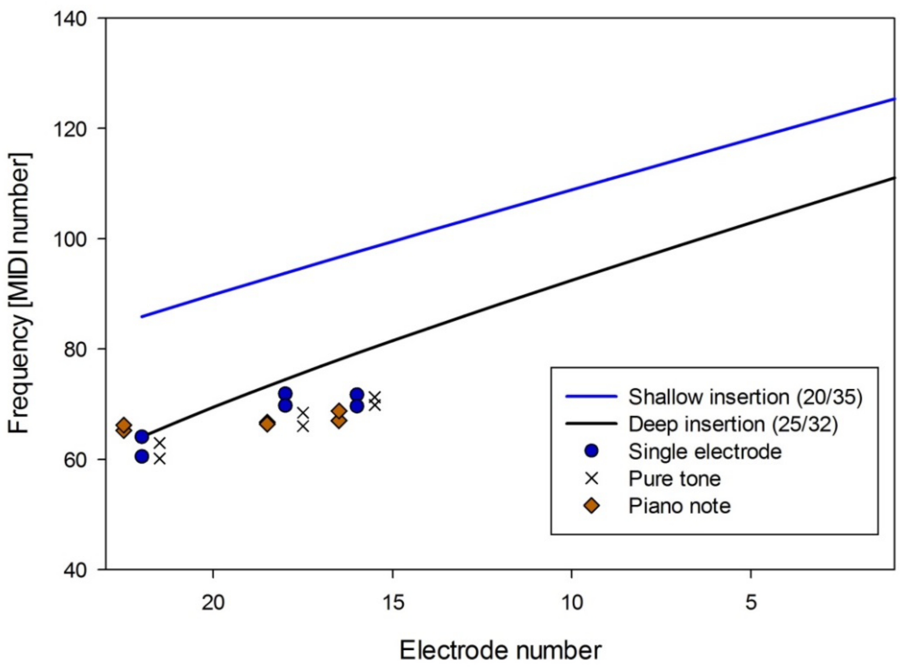

Figure 3-22: the mean matched frequency for Experiments A-2 to C-2 in relation to the range expected from Greenwood's function.

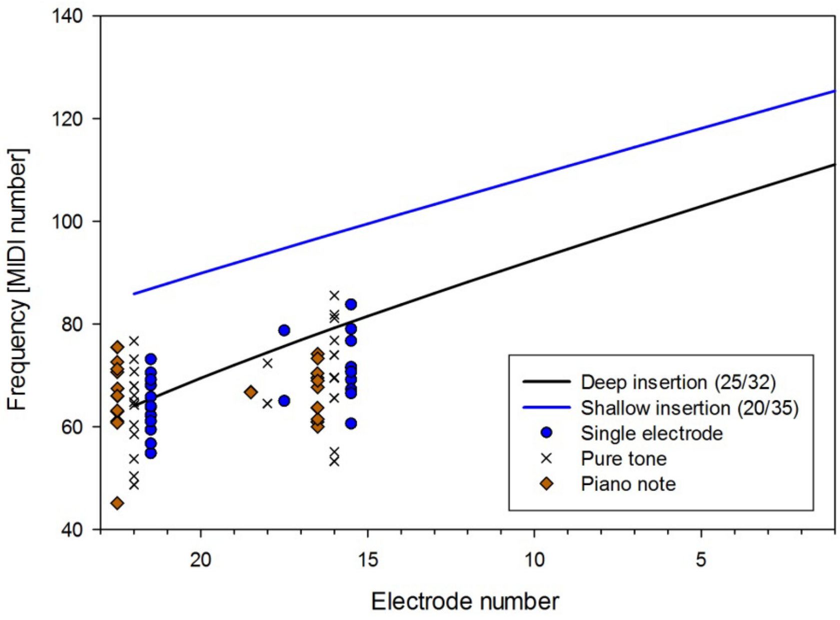

Figure 3-23: the mean matched frequency for each participant in Experiments A-2 to C-2 in relation to the range expected from Greenwood's function.

The perceived pitch for the high frequency stimuli in all six experiments was either consistent with the lowest prediction limit of Greenwood's equation or lower than the prediction span. This conclusion is in line with the finding of previous studies (Blamey, Dooley et al. 1996, Baumann and Nobbe 2006, Boëx, Baud et al. 2006, Dorman, Spahr et al. 2007), which measured the actual positions of the electrodes and concluded that the perceived pitch is always lower than the prediction by about an octave. The exact positions of the electrodes were not measured in the present study, so it is impossible to say how much lower the pitch is for individual participants. The reasons for the discrepancy between the results and Greenwood's function include the difference in lengths of the electrode array, the basilar membrane, and the ganglion neurons. As the ganglion cells fill more turns than the electrode arrays, and the low frequency ganglion cells are clustered around a position away from the apex of the cochlea in the middle turn, the most apical electrode would be adjacent to the low frequency ganglion cells and would therefore elicit lower pitches than expected. In addition, it is controversial whether electrode length or insertion angle is the best index to be used for the estimation of pitch of different electrodes because of variations of electrode array position which may hug the modiolus in the case of Contour electrodes, or be close to the outer wall of the scala tympani in the case of straight electrode arrays. The closeness of the electrode array to the neurons can introduce some inaccuracies in the estimation of the perceived pitch (Boëx, Baud et al. 2006, Stakhovskaya, Sridhar et al. 2007).

Carlyon, Macherey et al. (2010b) discussed the fact that the range of audibility of acoustical sounds in the non-implanted ear and the starting frequency of the acoustical sounds can influence the final matched frequencies in electric-acoustic pitch matching. In the present experiments, the stimulated electrodes were selected so that the acoustical sounds in the non-implanted ear would be audible in a frequency range which included the perfect matches. In addition, the starting frequencies of the acoustical sounds in the non-implanted ear were randomized. Therefore, the effects of these two factors were minimised. Despite being lower than expected, the perceived pitch for a stimulus with F0 of 250 Hz was higher in the implanted ear than in the non-implanted ear on average. Some studies have pointed to the possibility of plasticity in the auditory system so that over time the perceived pitch in electric hearing approaches the pitch associated with the acoustic frequency (Svirsky, Silveira et al. 2004, Reiss, Turner et al. 2007, McDermott, Sucher et al. 2009). On the other hand, there are other studies that do not support this kind of adaptation (Carlyon, Macherey et al. 2010b, Baumann, Rader et al. 2011). The results of the current experiments are consistent with the results reported in the studies which did not observe any adaptation. Therefore, it seems that there may always be a mismatch in pitch percepts of acoustic and electric hearing in a musical context as used in this study. One consequence of this mismatch is that for a single sound, there would be two different percepts in the ears with different modalities. Therefore for listening conditions in which perception of pitch is important (e.g., music perception and speech perception in noise) CI users not only do not have united pitch, but they also sometimes experience conflicting or contradictory pitches.

Although there is a shift toward low frequencies in the perceived pitch for the most apical electrode relative to the Greenwood function, this shift is not constant for all other electrodes. For an increase of 2 octaves in the F0s of the acoustical inputs (24 semitones), the perceived pitch changed just 13.5 semitones in experiments A-1, B-1 and C-1 and 10 semitones in experiments A-2, B-2 and C-2. This means that low frequency sounds in electric hearing are perceived higher than with normal acoustic hearing while high frequencies in electric hearing are perceived lower than with normal acoustic hearing. This indicates that a wide range of acoustic frequencies of 2 octaves was represented in approximately one octave in electric hearing for pure tones. The amount of frequency compression is even greater for complex sounds like musical notes (figure 3-4). This kind of compression has been reported in another study as well (Dorman, Spahr et al. 2007). Frequency compression would affect the relative distance between the harmonics of a complex signal and change the timbre of sound which is used in instrument recognition. One way to improve the representation of the harmonic structure of complex sounds may be to enhance the structure with a frequency expansion of the acoustic signals entering the sound processor. For instance, if the distance between the harmonics were increased, it may be possible to resolve the harmonic structure of complex tones and subsequently pitch perception may be improved. Omran, Lai et al. (2011) used frequency expansion, and their results showed smaller pitch difference limens in NH listeners who were tested with vocoder sounds. Kasturi and Loizou (2007) also showed improvement in melody recognition with such expansion in CI users when they used different numbers of channels (from 2 to 12) and filter bandwidth (from bandwidth of 6 semitones to 1 semitone). CI users showed significantly higher scores with a 12-channel and 1 semitone bandwidth compared to their daily processor. Swanson, Dawson et al. (2009) reported better melody recognition when the intervals of a melody were expanded up to 5 semitones since the participants of the study could not recognise the shift in melody intervals with the current speech processors when the shift was 2 semitones while they could recognise the shift when it was at least 5 semitones. Although frequency expansion improved music perception in these studies, it would be very difficult to apply clinically.

As the input sounds became more complicated, the difference between the perceived pitches of low and high frequencies became smaller. This is consistent with the place pitch perception model outlined in Chapter 1. As a single electrode or pure tone stimulus increases in frequency, the place of stimulation moves along the cochlea in accordance with the frequency-to-electrode map. The perceived pitch of a piano note may depend on the centroid of the stimulation pattern (the point at which the weight of low and high harmonics are in balance) which already includes high frequency electrodes, excited by the harmonics. As the fundamental frequency of the piano note increases, the centroid moves less than it does for a pure tone of the same frequency, and so the pitch change is smaller.

Figures 3-14 and 3-19 show the mean of the matched frequencies for each participant in all experiments at each frequency and intensity. The matched frequency values selected for each combination varied over a large range from one person to another. Such huge individual differences have also been reported in previous studies of pitch matching (Carlyon, Macherey et al. 2010b, Baumann, Rader et al. 2011, Green, Faulkner et al. 2012).

The individual differences are attributed to differences in insertion depth, the position of electrodes relative to their target neurons, the presence of ossification inside the cochlea, neural survival and dead regions in the non-implanted ear (Boëx, Baud et al. 2006, Stakhovskaya, Sridhar et al. 2007, Goldwyn, Bierer et al. 2010, Zhang, Dorman et al. 2014). As figure 1-3 of Greenwood's function shows, variations in the length of the cochlea and the insertion depth may account for differences of up to 20 semitones. However, the range of pitch matches was more than 20 semitones for some frequencies in some experiments. Another factor which can contribute to these individual differences is the presence of inactive electrodes which affect the frequency to electrode allocation in the map. For example, it is understandable that the perceived pitches of the pure tones and piano notes for participants S2 and S8, who have 3 and 2 inactive electrodes respectively, would be different from those for others because their frequency allocation tables were different. Common reasons for inactive electrodes include non-auditory sensations when these electrodes are stimulated, and/or short insertion depth, which leaves some of the basal electrodes outside the cochlea. When electrodes are inactive, frequencies are reallocated so that the fixed range of acoustic inputs stimulates fewer active electrodes. For people whose electrode arrays are close to the modiolus, the targeted neurons may be stimulated more precisely than for some people whose electrode arrays are close to the lateral wall of the cochlea. In this case, different perceived pitches for a given electrode would not be surprising. The formation of ossification may change the current flow and the perceived pitch elicited by stimulation of some electrodes. Even with ideal positioning of the electrodes, it is possible that there may not be enough surviving neurons close to the electrode to elicit the desired pitch percept. In this case, the neurons with CFs away from target will respond. Unfortunately, there is no standard and widely accepted way to measure neural survival (Goldwyn, Bierer et al. 2010).

Another possibility for different perceived pitch in different people is the presence of a dead region in the non-implanted ear. As described in chapter 1, one effect of dead regions is off-frequency hearing. In this case, the perceived pitch match for a CI user with a dead region in the non-implanted ear may be different from that of a CI user who has functioning hair cells throughout the relevant frequency region.

Effects of loudness on perceived pitch

Hypothesis 2 stated that increased intensity would decrease the perceived pitch of high frequency sounds or the more basal electrode.

The effect of intensity was not significant in any of the three experiments of A-1, B-1 and C-1, while in table 3-1, the ANOVA indicated a significant effect for intensity. Table 3-1 summarised the general effects of possible factors on the matched frequency in all six experiments while the large dataset was broken into six smaller datasets specific to each experiment and the ANOVA for experiments A-1to C-2 were shown in tables 3-5 to 3-10. Based on the residual Mean Square (MS) in table 3-1 and the number of trials for each level of intensity (n=432), the estimated standard error of the difference between soft and loud would be ($\sqrt{\frac{68.4}{432}}$=0.39) 0.39. Therefore the minimum effect of loudness on the perceived pitch which would be detectable is 0.77 MIDI notes (1.96*0.39= 0.77). The mean of the perceived pitch for loud sounds was 68.80 MIDI numbers and for soft sounds was 70.05 MIDI numbers. The power for detecting this difference was 0.60. The difference in the perceived pitches of soft and loud sounds was bigger than the minimum detectable effect, so the general analysis could detect the significant effect (the effect of intensity was significant when all the data were analysed). On the other hand, the smaller datasets did not have enough power to show the main effect of intensity (power dropped to 0.2 when the dataset was divided into six small datasets). In addition, large changes in different directions for different Participants may have obscured the main effect of intensity.

Inspection of figure 3-4 shows that the average perceived pitch of the more basal electrode or the higher frequency did not decrease significantly with increases in intensity except for experiment A-1. This means that hypothesis 2 was supported only for experiment A-1. Examination of the green bars in figures 3-14 to 3-19 shows that there was great individual variability, and there were 6 Participants in Experiment A-1, 4 Participants in Experiment B-1, 3 Participants in Experiment C-1, 2 Participants in Experiment A-2, 4 Participants in Experiment B-2 and 2 in Experiment C-2 with 7 to 15 semitones pitch decreases for the high frequency stimuli at loud levels, supporting Hypothesis 2 for these individuals.

In single electrode stimulations of the more basal electrode, when intensity increases, more neurons are involved in coding of pitch. Therefore the surrounding neurons are expected to receive stimulation. Since most CI users have had a high frequency hearing loss for a long time, it is expected that higher frequency neurons would have been damaged more than the lower frequency neurons. Therefore, lower pitch perception of the more basal electrode was hypothesized. For experiment A-1, lower pitch at higher intensities was observed for high frequency electrodes as shown by the confidence interval in Figure 3-4.In contrast, there was no significant difference for the corresponding high frequency stimuli in experiment A-2. The different results for A-1 and A-2 indicate that the pure tone and complex tones in the non-implanted ear had different perceived pitches. The difference between experiment A-1 and A-2 is their Adjustable sounds. The cochleae of non-implanted ears were damaged. The Adjustable sounds were presented to these ears with damaged cochleae and the changes in the perceived pitches of the implanted ear were expected to show themselves in the frequency of the Adjustable sounds. For people with damaged cochleae, the pitch discrimination of sinusoid signals (like pure tones) is better than that of complex sounds (Penninger, Chien et al. 2013).

It is plausible that the greater variability in the perception of pitch for complex sounds reduced the statistical significance of the effect of intensity in Experiment A-2. The individual results indicate that the assumption that neural survival would be greater in the more apical regions than in the basal regions of the cochlea was only true for some participants. There is little literature on the patterns of neural survival in deaf or hearing impaired cochleae, but a few studies show highly variable and patchy survival patterns (Incesulu and Nadol 1998) . Variable, patchy neural survival may help to explain the highly variable effects of intensity on pitch matches for loud and soft sounds at low and high frequencies across individuals. Other factors like the effects of residual hearing and the initial frequency presented to the implanted ears have been suggested for such variability but it has been shown that they were not very plausible reasons (Carlyon, Macherey et al. 2010b, Green, Faulkner et al. 2012).

As figures 2-3 to 2-8 show, neighbouring electrodes on both sides of the target electrode receive stimulation as intensity increases. Current spreading and electrode activation spreading can go in both basal and apical directions for the high frequency Reference pure tones. Thus the effect of intensity on the high-frequency pure tones was expected to be similar to its effect on the basal single-electrode stimuli. Visual inspection of the green bars in figures 3-14, 3-15, 3-17 and 3-18 indicates that this expectation is not supported by the data.

Figure 2-9 shows that even for soft sounds, the neurons of more basal regions of the implanted ear will receive simulation as a result of the harmonics of the piano note. This was expected to result in higher pitch matches for piano notes in Experiments C-1 and C-2 than for single electrodes and pure tones in Experiments A-1, B-1, A-2, and B-2. The opposite of this expectation was observed for the high frequency Reference sounds. It seems evident that at higher intensity, the three kinds of spread would act together and may not allow small changes in pitch to be detected. This is expected to have a detrimental effect on the perception of musical notes which are complex signals and which cover a very large range of intensities in music. The effects are not expected to be so great in speech perception where pitch is less important, and where additional information from vision (lipreading) and language knowledge can help to guess missing parts.

Another consequence of electrode activation spread in experiment B-1 and B-2 and spectral spread in experiments C-1 and C-2, is that sounds presented to the implanted ear may have added some noisy quality to the perceived pitches as a result of the involvement of more electrodes even for pure tones and unresolved harmonics of complex tones in coding pitches. This noisy quality can also prevent people from monitoring changes in pitch. This noisy quality has been also reported in single electrode stimulations as well (Baumann, Rader et al. 2011) but it is expected to be more problematic in pure tone or piano note sound representation.

Inspection of the confidence intervals in Figure 3-4 indicates there was no statistically significant change in the average perceived pitch with loudness of the low frequency sounds (experiments B and C) or most apical electrode (experiments A-1 and A-2). Examination of the yellow bars in figures 3-14 to 3-19 shows that there was great individual variability, but there were 6 Participants in Experiment A-1, 6 Participants in Experiment B-1, 5 Participants in Experiment C-1, 4 Participants in Experiment A-2, 5 Participants in Experiment B-2 and 8 Participants in Experiment C-2 with large pitch increases or decreases for the low frequency stimuli at loud levels, rejecting Hypothesis 2 for these individuals.

In essence, the unpredictable neural survival patterns in the vicinity of the electrodes used to present the Reference stimuli may lead to unpredictable effects of Intensity on the matched pitch frequencies for Participants and Frequencies in all experiments.

It was hypothesized that the difference of the matched frequencies selected for low and high frequencies would be greatest for the single electrode and pure tone Reference Types (Experiments A-1, B-1, A-2 and B-2) and least for the piano note Reference Type (Experiments C-1 and C-2). It is clear from figure 3-4 that the perceived pitches of low and high frequencies were significantly different in experiments A-1, B-1, A-2 and B-2. The differences between the perceived pitches of low and high frequencies were not significant in experiments C-1 and C-2.

By looking at figure 2-9 we can see many electrodes are involved in coding of piano notes even at soft levels. In contrast, the excitation patterns produced by single electrode stimulation and pure tone stimuli will be much narrower even after allowing for current spread and electrode activation spread. The narrower distribution will not overlap for low and high frequency stimulation, but there will be considerable overlap for low and high frequency piano notes coded by the CI.

Similarity ratings

These hypotheses predicted that the similarity ratings for the complex tone Adjustable Type would be higher than for the pure tone Adjustable Type in the corresponding experiments (A-1 compared with A-2, B-1 compared with B-2, and C-1 compared with C-2). Regardless of the type, intensity and frequency of stimulus presented to the implanted ear, the similarity ratings were lower when the Adjustable sounds were complex tones as shown in Table 3-3. The only exception was for the rating of experiment A-1 at the low frequency. Table 3-4 indicates that the pairwise comparisons were not significant. These systematic lower ratings in experiments A-2, B-2 and C-2 in which the Adjustable sounds were complex tones are contrary to the report of Lazard et al. (2012). In a similar matching experiment, Lazard and colleagues asked their bimodal participants to change the centre frequency and Q factor for a filtered acoustic sound presented to the non-implanted ear in order to find the most similar sound to a pulse train presented to the most apical electrode in the implanted ear. The pulse trains were tested against harmonic, inharmonic complex sounds and band-pass noises as the acoustic adjustable sounds. They reported that a filtered harmonic complex sound was the most similar sound to an electric pulse train presented to the most apical electrode. The complex tone Adjustable Type used for the experiments in this thesis was modelled on the filtered harmonic complex of Lazard et al (2012). While they instructed participants to find "the most similar sound to an electric pulse train" just for the most apical electrode, experiments A-1 and A-2 tested similarity of matches for different electrodes. Another difference between the current study and Lazard et al's study was that the similarity ratings were recorded for different intensities and stimulus types which were presented to the implanted ear while they administered their test at most comfortable level. The similarity of sounds is influenced by both spectral and temporal aspects of sound. Hearing loss in the non-implanted ears could render the spectral aspects of sounds less salient as a result of the reduced frequency selectivity of the impaired ear (Moore 1998). It has been reported that in both CI users and people with hearing loss, temporal envelope cues are more salient and reliable than spectral cues for musical timbre perception (Kong, Mullangi et al. 2011, Kong, Mullangi et al. 2012). On the other hand, the spectral shape of a pure tone in the non-implanted ear is not changed with hearing loss while the perception of a complex tone may be altered due to poor frequency selectivity which may not allow harmonic structure to be resolved (Moore and Peters 1992) and by variations in thresholds across frequency. Therefore the effect of cochlear damage on a pure tone is less than on a complex tone. This may help to explain why the participants in the present study had higher similarity scores at matching points when a pure tone was presented to the non-implanted ear rather than a complex tone when they matched pitch and loudness.

The results of the matching and rating experiments show that the degree of hearing loss in the non-implanted ear can also affect the perception of pitch. Therefore, for the same sound reaching both the implanted and non-implanted ears there could be two different pitch percepts, not only because of the effects of electrical stimulation, but also because of the damaged hearing of the non-implanted ear and the fitting of the hearing aid. For example, as people have different degrees and shapes of hearing loss and different frequency responses for their HAs, the same sound may be subjected to different frequency filtering effects. This could change pitch and possibly melody recognition and stream segregation of different melody lines as they are pitch-related tasks. In addition, the harmonic structure of musical sounds plays an important role in instrument recognition. Some instruments within an instrument genre can be recognised by the discrimination of some higher harmonics. If higher harmonic information is lost due to hearing loss or filtering of a HA, these instruments cannot be recognised reliably.

It should be remembered that the Beam, Whisper, and ADRO pre-processing options were disabled in the psychophysical matching experiments. The main effects of these options are to change the intensity of some parts of the signal relative to others prior to sound processing in the CI. The pre-processing programs in speech processors are useful in noisy situations while the experiments were done in a quiet environment in a sound-proof booth. Therefore there would not have been any difference in the quality of sounds presented to if these pre-processing programs had been on. In a loud or noisy environment, pre-processing could affect overall loudness and/or spectral shape. The current experiments suggest the overall loudness would have a relatively small effect but the spectral shape change may have a relatively large effect on perceived pitch in the implanted ear.

In summary, the main hypotheses of the study were supported by the results. Some of the specific hypotheses were supported and others were rejected, but the pattern of results has led to an improved understanding of the interaction of cochlear implant and sound processor characteristics. This information can be used in studies of individual differences in neural survival and insertion depth to explain why loudness can change the perception of pitch. The consequences of these interactions are that melody perception with CIs is complicated by distortion of the pitch of a musical note depending on the type and intensity of the note as well as its frequency. Furthermore, the pitch of musical notes is shifted in a CI relative to the original acoustic note because of variations in cochlea length and insertion depth in individuals. For bimodal listeners, this frequency shift and the complexities of pitch perception in both ears may lead to hearing different pitches and different melodies in the two ears.

Chapter 4: Within-modality matching

Introduction

In the electro-acoustic pitch matching experiments, the participants had to listen to the pitch of sounds presented to their implanted ear and then find the matching pitch in their non-implanted ear. There are some studies of the change in perceived pitch with intensity in CI users (Shannon 1983, Townshend, Cotter et al. 1987, Pijl 1997, Arnoldner, Riss et al. 2008, Carlyon, Lynch et al. 2010). These studies have been conducted with people who had only electric hearing. The increase in the number of people who have residual hearing in their non-implanted ear provides the opportunity of monitoring the potential changes in pitch with changes in intensity in the non-implanted ear. The experiments of chapter 3 were designed to use this opportunity. The experiments were designed with the assumption that if there was a change in the perceived pitch of the implanted ears (in electric hearing), there would be similar change in the perceived pitch of the non-implanted ears (acoustic hearing). Cochlear hearing loss may impair pitch perception ability in some people, while others may have near-normal pitch perception (Moore and Carlyon 2005), but it is assumed that most people with residual hearing can perceive pitch of a sound when it is audible (Florentine and Houtsma 1983, Turner, Burns et al. 1983). In normally-hearing listeners, despite some large individual differences, the perception of pitch in acoustic hearing changes negligibly with the intensity of sounds (Morgan, Garner et al. 1951, Verschuure and Meeteren 1975) but studies on people with sensorineural hearing loss have shown various results from small effects of intensity on pitch to big effects in some cases (Burns and Turner 1986). Although the bimodal CI users who participated in pitch matching experiments had reasonably good residual hearing, there may be some questions about the reliability of electro-acoustic pitch matching. The questions that might arise include: “Did the participants have reliable pitch discrimination ability in their non-implanted ear?” “How did the perception of pitch in the non-implanted ear change when the intensity of sounds changed?”

Most studies about the effect of intensity on the perception of pitch have been done on electric hearing (in CI users). In these studies, some participants showed a big effect of intensity on the perceived pitch and some did not in bimodal pitch matching. Therefore, a similar question might be posed about the perception of pitch in different levels of intensity in just the implanted ears: “How did the perception of pitch in the implanted ear change when the intensity of sounds changed?”

To answer these questions, two experiments were designed to investigate the perception and possible changes of pitch at different levels of intensity in each ear separately. The results of these experiments provide further insight into the electric-acoustic pitch matching. The pitch matching experiments in each ear are called “monaural pitch matching” in this thesis.

Method

Pitch matching in the non-implanted ear

Nine people who also participated in the experiments of chapter 3 participated in this experiment. S3, S5 and S7 were not available to participate. Among the participating people, two, (S10 and S12) had hearing thresholds above 90 dB at 1 KHz. All other participants had hearing thresholds below 90 dB in a range of frequencies up to 1 KHz. All the demographic information about the participants and the information about their CIs and HAs can be found in the Method section of chapter 3.

The task in this experiment was a monaural pitch matching task which was carried out in the non-implanted ear. The test took 45 minutes. Two sounds were presented consecutively to the non-implanted ear. The loudness of the Reference and Adjustable sounds was determined prior to the test using a 7-step loudness scale. Using this scale, they rated their loudness sensation from very soft to very loud. The Reference sound was always “soft” and the Adjustable sound was always “loud”. Both the Reference and Adjustable sounds had similar stimulus type (pure tone or complex tone). The order of the presentation of the reference sounds was completely randomized. The similarity in the type of the Reference and Adjustable sounds meant that the only difference between the two sounds was in the difference in intensity. The participants could not change intensity, as the task was to match only pitch of the louder Adjustable sound to the pitch of the softer Reference sound.

The matching was done for a low frequency and a high frequency Reference sound. For each of low and high frequencies, three matching trials were recorded. The total number of matching trials for each participant was 12 (2 frequencies * 2 sound types * 3 repetitions). For matching at low frequency, 250 Hz was used for all participants. For matching at high frequency, except for S10 and S12, the participants matched the Adjustable sounds to a 1 kHz Reference sound. As they had hearing thresholds above 90 dB at 1 kHz, S10 and S12 matched the Adjustable sounds with 750 Hz Reference sounds. All stimuli were created, controlled and presented using MAX/MSP 6.

Before the test started, the equivalent intensities with soft and loud sounds were recorded for both low and high frequencies using a loudness scale with seven points from too soft to too loud. Both Reference and Adjustable sounds were delivered to the non-implanted ear with an insert phone which was inserted deeply in the ear. Before presenting the sounds, the NAL-RP hearing prescription (Byrne, Parkinson et al. 1990) was used to compensate for the effect of hearing loss by assignment of the required gain at each frequency.

The participant was asked to turn a knob to change the F0 of the Adjustable sounds after listening to the Reference sounds (the soft sounds). Turning the knob changed the frequency of the Adjustable sounds. The values recorded as final matches were assumed to be physical correlates of the perceived pitch. For each trial, the starting frequency of the Adjustable sound was randomized. The range in which the participants could change the F0s of the Adjustable sounds was 1 octave, and included the F0 of the Reference sound. After each matching trial, the participants were asked to rate the similarity of the Adjustable sound to the Reference sound. A rating scale from 0 to 25 was used for rating task.

The monaural acoustic experiment was performed when the Reference and Adjustable Types were pure tones, and again when the Reference and Adjustable Types were complex tones.

Pitch matching in the implanted ear

Eight people who participated in the bimodal experiments also participated in this experiment. S2, S3, S5 and S7 were unavailable. Like the experiment of pitch matching in the non-implanted ear, the task was to match the pitch of a loud Adjustable sound to the pitch of a soft Reference sound. The order of presentation of the Reference frequencies and sound types was completely randomized and the Adjustable sounds were presented with an intensity level described as "loud but tolerable". Both sounds were presented to the implanted ear.

The matching task was done at low and high frequencies selected for each participant as in the bimodal and monaural acoustic pitch matching experiments. There were 12 trials for each participant (2 frequencies * 2 sound types * 3 repetitions). For each trial, the starting frequency of the Adjustable sound was randomized. The range in which the participants could change the F0s of the Adjustable sounds was one octave, which included the F0 of the Reference sound.

Both the Reference and Adjustable sounds were sent through DAI to a Freedom sound processor which was programmed with the latest map for each participant. The participants listened to the sounds through the map they used every day while the pre-processing programs were deactivated.

The monaural electric experiment was performed when the Reference and Adjustable Types were pure tones, and again when the Reference and Adjustable Types were complex tones. After each matching trial, the participants were asked to rate the similarity of the Adjustable sound to the Reference sound. A rating scale from 0 to 25 was used for the rating task.

Results

Monaural pitch matching in non-implanted ear

Table 4-1 shows the ANOVA results for pitch matching in the non-implanted ear. It shows that the matched frequency for different Reference frequency was statistically significant (df=1, F=929 and $p < 0.001$). In addition, the matched frequencies selected by different people were significantly different and there was a significant interaction between Reference frequency and Participant. Due to the relatively small number of trials, the three-way interaction of Reference frequency, Adjustable type and Participant was not calculated.

Variable	df	MS	F ratio	P value
Reference frequency	1	9408.32	929.52	<0.001
Adjustable type	1	12.05	1.19	0.279
Participant	8	37.95	3.75	0.001
Reference frequency*Adjustable type	1	20.52	2.03	0.159
Reference frequency*Participant	8	40.79	4.03	0.001
Adjustable type*Participant	8	11.9	1.18	0.325
Residual	73	10.12		
Total	100			

Table 4-1: ANOVA of matched frequency for within modality pitch matching in the non-implanted ear

Pure tone

Figure 4-1 shows the individual matched frequencies selected by the participants when both Reference and Adjustable sounds were pure tones and presented to their non-implanted ears. The high frequency for two participants was 750 Hz and 1 KHz for the others.

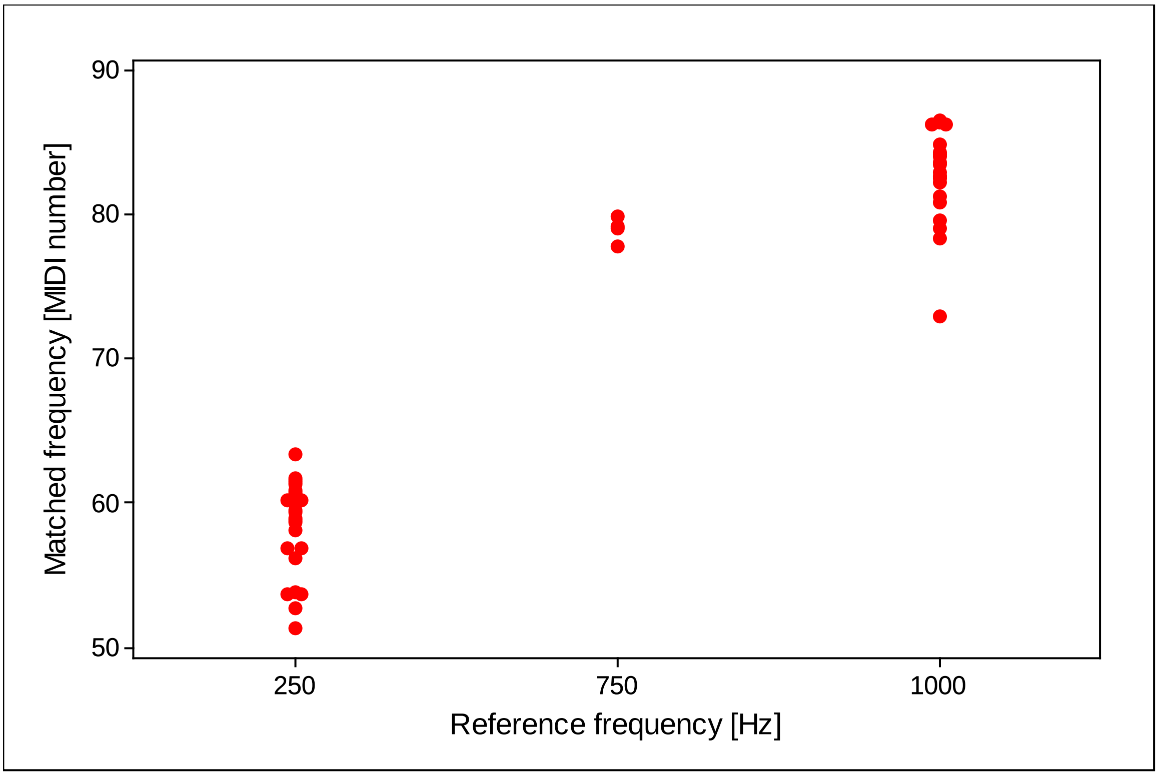

Figure 4-1: the distribution of the matched frequency in MIDI number selected for different frequencies of the Reference sounds when both Reference and Adjustable sounds were pure tones in the non-implanted ear

This figure indicates the matched frequencies of low (with MIDI number of 59) and high frequencies (with MIDI numbers of 78 and 83) as the Reference sounds were pure tones.

The mean of the matched frequency for low frequency was 58.49 with a standard error of 0.621 MIDI number. A 95% confidence interval was made for low frequency which had a range from 57.27 to 59.70 MIDI number (from 223 to 257 Hz). Since the equivalent MIDI number of 250 Hz was 59.21, it showed that the range of the matched frequency included 250Hz. This means that the matched frequencies selected for low frequency Reference sounds did not differ significantly from 250 Hz.

For a high frequency of 1 kHz, the participants selected a 95% confidence interval from 78.43 to 82.18 MIDI number (from 753 to 942 Hz) with an average of 80.46 MIDI number (853 Hz) and standard error of 0.881 in MIDI number. This range did not include

1 kHz. This means that the matched frequencies selected for the high frequency Reference sounds differed significantly from 1000 Hz when the Reference and Adjustable sounds had different levels of intensity.

For the high frequency of 750 Hz, the 95% confidence interval was from 79.56 to 81.65 MIDI number (from 809 to 913 Hz). The mean of the matched frequency was 80.6 MIDI number (859 Hz) with standard error 0.535in MIDI number. The equivalent MIDI number of 750 Hz (78.23) was not found in this range.

Complex tone

Figure 4-2 depicts the distribution of the matched frequency selected by the participants when both Reference and Adjustable sounds were complex tones presented to their non-implanted ears.

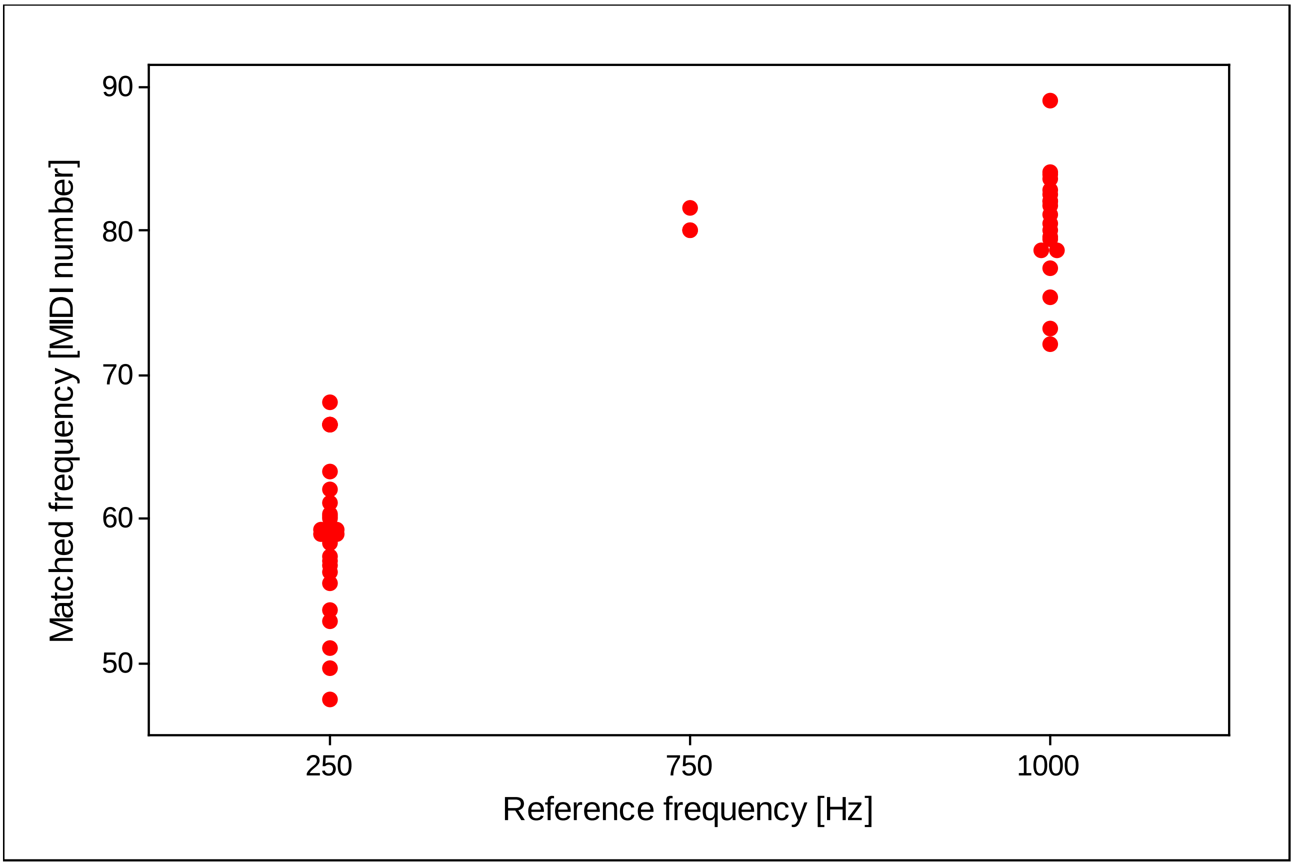

Figure 4-2: the distribution of the matched frequency of 9 participants in MIDI number selected for different frequencies of the Reference sounds when both Reference and Adjustable sounds were complex tones presented to the non-implanted ear

The mean of the matched frequency for low frequency was 58.75 MIDI number (243 Hz) with the standard error of 0.97 MIDI number. The 95% confidence interval was from 56.85 to 60.65 MIDI number (from 218 to 271 Hz) . This range included the equivalent MIDI number of 250 Hz which is 59.21.

The range of the matched frequency for 1 kHz was from 78.73 to 82.18 MIDI number (from 771 to 942 Hz) which did not include the equivalent MIDI number of 1 kHz. The mean was 80.46 (852 Hz) and the standard error was 1.72 in MIDI number.

The range of the matched frequency for 750 Hz did not include 78.23 which is the MIDI number of 750 Hz. The 95% confidence interval was from 79.56 to 81.65 MIDI number (809 to 913 Hz) with a mean of 80.60 MIDI number (859 Hz) and the standard error of 0.535 in MIDI number.

	Reference frequency		
	250 Hz	750 Hz	1000 Hz
pure tone	86.92%	89.5%	89.90%
complex tone	84.81%	93.33%	86.19%

Table 4-2: the mean rating for different frequencies and different types of sounds when the matching was done in the non-implanted ear

The first row which is pure tone refers to the situation in which both Reference and Adjustable sounds were pure tones and the second row is related to when both Reference and Adjustable sounds were complex tones.

Table 4-2 shows the mean rating in percentage for both pure tone and complex tone conditions for all the Reference sounds. There were no significant differences in the similarity ratings between frequencies or stimulus types.

Monaural pitch matching in the implanted ear

Table 4-3 shows the ANOVA results for pitch matching in the implanted ear. It shows that the matched frequencies for different Reference frequencies were statistically significantly different (df=1, F=2.41 and p value<0.001).

Variable	df	MS	F ratio	P value
Reference frequency	1	9710.61	469.59	<0.001
Adjustable type	1	19.72	0.95	0.332
Participant	7	82.44	3.99	0.001
Reference frequency*Adjustable type	1	55.73	2.7	0.106
Reference frequency*Participant	7	36.63	1.77	0.109
Adjustable type*Participant	7	63.7	3.08	0.007
Reference frequency*Adjustable type*Participant	7	50.88	2.46	0.027
Residual	64	20.68		
Total	95			

Table 4-3: ANOVA of the matched frequency for within modality pitch matching in the implanted ear

Pure tone

Figure 4-3 shows the distribution of the matched frequency in the monaural pitch matching experiment with pure tones in the implanted ear.

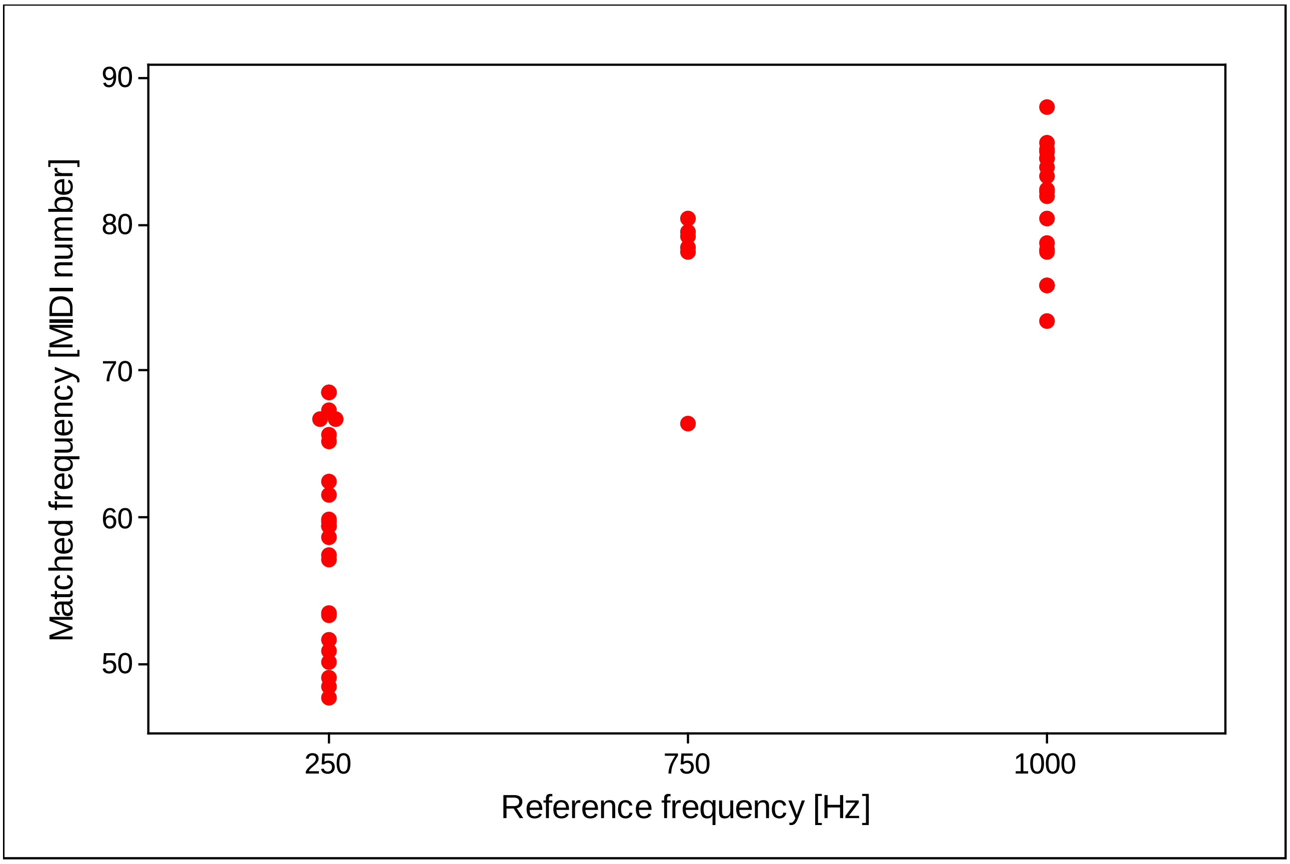

Figure 4-3: the distribution of the matched frequency of 8 participants in MIDI number selected for different frequencies of the Reference sounds when both Reference and Adjustable sounds were pure tones. The matching was done in the implanted ear

The mean and standard error for low frequency were 58.79 (243 Hz) and 1.4 MIDI number respectively. The 95% confidence interval of the mean was from 56.05 to 61.53 in MIDI number (from 208 to 285 Hz). Since the MIDI number of 250 Hz (59.21) lay in this range, there was no significant difference between the matched frequency selected for low frequency and 250 Hz.

Similarly, the participants selected a close matched frequency for the high frequency Reference (either 750 Hz or 1000 Hz). The mean of the matched frequency selected for the 1000 Hz Reference sound was 81.55 MIDI number with a standard error of 0.94. Since the

Reference frequency lay within the 95% confidence interval of the mean (79.67 to 83.43 MIDI number corresponding to 814 to 1012 in Hz), the average matched frequency selected for l000 Hz was not significantly different from 1 kHz.

The mean of the matched frequency for 750 Hz was 77.07 (701 Hz) with a standard error of 2.15 MIDI number. Statistical analysis showed that the difference between the matched frequency and 750 Hz was not significant.

Complex tone

Figure 4-4 demonstrates individual pitch matches for the Reference sounds against the MIDI numbers selected as matched frequencies when both the Reference and Adjustable sounds were complex tones and were presented to the ear with a CI.

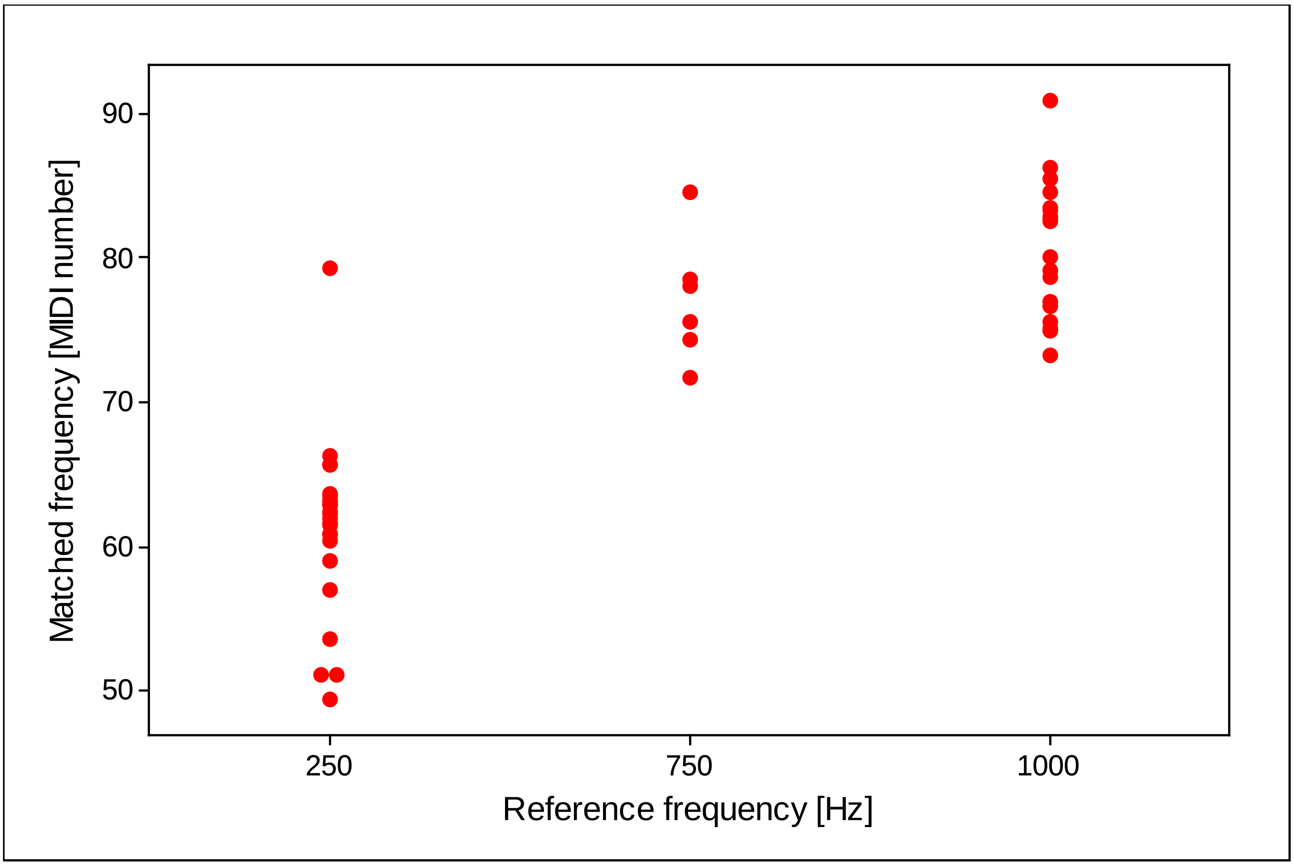

Figure 4-4: the distribution of the matched frequency in MIDI number selected for different frequencies of the Reference sounds when both Reference and Adjustable sounds were complex tones. The matching was done in the implanted ear

The participants matched the low frequency of 250 Hz with a mean of 61.51 MIDI number (285 Hz) and standard error of 0.95. The 95% confidence interval for low frequency included the MIDI number equivalent to 250 Hz (59.21) which indicated that there was no significant difference between the matched frequencies and 250 Hz.

The matched frequency selected for 1000 Hz was significantly different from 1000 Hz since the 95% confidence interval for this frequency did not include the MIDI number equivalent for 1000 Hz. The mean of the matched frequency was 80.17 MIDI number (838 Hz) with a standard error of 1.12 in MIDI number. The softer sound was perceived as having a lower pitch than the louder sound on average.

The mean of the matched frequency for 750 Hz was 77.13 MIDI number (703 Hz) with a standard error of 1.80 MIDI number. Statistical analysis showed that the difference between the matched frequency and 750 Hz was not significant.

	Reference frequency		
	250	750	1000
pure tone	81.83%	66.33%	87.56%
complex tone	76.17%	69.67%	85.78%

Table 4-4: the mean similarity rating for different frequencies and different types of sounds when the matching was done in the implanted ear

The first row refers to the situation in which both Reference and Adjustable sounds were pure tones and the second row is related to when both Reference and Adjustable sounds were complex tones.

Table 4-4 summarises the mean similarity ratings for different frequencies and different types of sounds. The lowest mean was for 750 Hz in both types of sound (pure tone and complex tone). There was a significant difference between the rating of 750 Hz and that of the other two frequencies (250 Hz and 1000 Hz).

There was no significant difference between the rating of similarity for pure tones and complex tones although the mean rating for pure tones was slightly higher than that for complex tones (82% versus 79%).

Variability of pitch matching in between- and within- modality experiments

ANOVA tests the differences of means between groups against the observed variability within groups. In a table of ANOVA the Mean Square (MS) for each group is shown, in addition to the residual MS which is assumed to be the variability due to chance. If the ratio of the MS of a factor to the residual MS is bigger than a critical F value, the systematic variability between groups is larger than the variability within groups and the difference is statistically significant (Howell 2010).

The F test can also be used to assess the ratio of any two variances (or mean squares) for significance. The residual MS for the pitch matching experiments in the implanted ear was 35.47 with df = 96 (Table 4-3) while for the experiments in the non-implanted ear the residual MS was 18.82 with df = 101 (Table 4-1). The ratio of these two values is 1.88. This ratio was compared to the critical value for the dfs of 96 and 101 in the F distribution table which was 1.39. As 1.88 was larger than 1.39, the participants showed significantly more variability in the perceived pitch in the implanted ear in comparison with the non-implanted ear ($p<0.05$).

Similarly, comparison of the residual MS in Tables 3-1 and 4-3 shows there was significantly greater variability in the between matching experiments than in the implanted ear matches ($F(576,96) = 1.92 > 1.31$, $p<0.05$).

In general, the variability of the perceived pitch for between-modality pitch matching was significantly higher than that of both within-modality pitch matching experiments. In within-modality pitch matching, the participants showed more variable pitch perception in the implanted ear in comparison with the non-implanted ear.

Discussion

The mean results of the monaural pitch matching experiments showed no effect of intensity at the low frequency for either stimulus type or either modality. At 1 kHz, the loud sound had significantly higher pitch than the soft sound for acoustic pure tones, acoustic complex tones, and electric complex tones, but not for electric pure tones. For the 750 Hz Reference, the softer sound had higher pitch than the louder sound for the acoustic stimuli, but not for the electric stimuli. The similarity ratings tended to be higher for pure tones than for complex tones and for acoustic compared to electric stimuli. These results are in reasonable agreement with the literature and with the results of the bimodal pitch matching experiments as discussed below.

Some caution should be exercised in the interpretation of the monaural pitch matching results. Not all participants of the bimodal pitch matching were available for the monaural pitch matching, reducing the power of the test. Moreover, the frequency range of the

Adjustable sounds in the bimodal pitch matching was wider than that for the monaural pitch matching. The only differences between Reference and Adjustable sounds were the intensity (fixed soft and loud sounds) and the frequency of the Adjustable sounds. This was not the case for the bimodal pitch matching where there were additional timbre and modality differences. Finally, since there is always some chance that the quality or timbre of sounds contributes to the perception of pitch, the amount of this contribution in bimodal pitch matching might be different than in monaural pitch matching.

Cochlear hearing loss may impair pitch perception in some people and yet near-normal pitch perception may be preserved in other cases (Moore and Carlyon 2005). However, it is usually assumed that people with residual hearing can perceive the pitch of a sound when it is audible (Florentine and Houtsma 1983, Turner, Burns et al. 1983). In normally-hearing listeners, despite some large individual differences, the perception of pitch in acoustic hearing for most of people changes negligibly with the intensity of sounds (Morgan, Garner et al. 1951, Verschuure and Meeteren 1975) but studies on people with sensorineural hearing loss have shown various results from small effects to big effects in some cases (Burns and Turner 1986).

Hearing loss with cochlear origin may impair the perception of pitch but it does not have a direct relationship with hearing thresholds, and large individual differences are observed (Larkin 1983).

In accord with the above literature, the monaural pitch matching results showed that the perception of pitch in the ears with residual hearing did not change greatly with intensity in the participants of these experiments. Despite the difference in intensity, they selected frequencies close to the Reference frequency. There were some significant changes in pitch with intensity for the high frequency acoustic stimuli, in accordance with the literature. The changes could be in either direction, depending on the individual participant, as shown by the different results for participants tested at 750 Hz or 1 kHz. Hearing impairment, dead regions and/or missing outer hair cells and damaged inner hair cells at high frequencies are likely to contribute to these individual differences.

A strong implication of this result is that the participants in the bimodal experiments could perceive the correct pitch in the non-implanted ear for at least the low frequency despite their hearing loss. It is possible that the lower thresholds account for the higher similarity ratings at low frequencies. Even at the high frequency, the matched frequencies were quite close to the Reference frequency. This implies that the relatively large effects of intensity on pitch matching in the bimodal experiments were unlikely to be caused by factors associated with the non-implanted ear, and must have originated in the implanted ear or the CI sound processor.

The rating of similarity for the monaural acoustic matches was high compared with many of the bimodal matches and the monaural electric matches. This is consistent with the smaller standard errors and narrower confidence intervals found for the acoustic matches than for the bimodal matches and monaural electric matches.

On average for monaural pitch matching in the implanted ear, the participants selected a matched frequency close to the Reference frequency except for the 1 kHz complex tone condition. However, the range of matched frequencies tended to be greater for the electric stimuli than for the acoustic stimuli, perhaps indicating the different mechanisms underlying pitch perception and the influence of intensity in these two modalities. The broad range of pitch matches in the CI ear is consistent with the strong individual differences observed in the bimodal experiments.

There was no significant difference between the mean similarity ratings for the frequencies of the Reference sounds or the types of stimuli. However, the scores were higher for pure tones and high frequency. The mean similarity ratings for electric hearing were lower in comparison with the similarity ratings for monaural pitch matching in the non-implanted ear, which may point to lower pitch perception ability of the participants in electric hearing.

Chapter 5: Conclusion

CIs have originally designed to improve the perception of speech in hearing-impaired people. While the perception of speech with CIs can meet the expectation of the majority of CI users, their experiences with musical sounds are often so unsatisfactory that some of them do not enjoy listening to music at all (Migirov, Kronenberg et al. 2009, Wright and Uchanski 2012). There have been many lines of research designed to solve the music perception problem or at least improve musical enjoyment (Gfeller, Witt et al. 2000, Vandali, Sucher et al. 2005, Hochmair, Nopp et al. 2006, Laneau, Wouters et al. 2006, Swanson 2008, El Fata, James et al. 2009). It is thought that the problem is in the poor perception of musical elements which make up a musical piece. From this perspective, the main constituents of music are rhythm, pitch and timbre. Many authors have tried to assess these elements of music in the population of CI users(Gfeller, Witt et al. 2002, Gfeller, Olszewski et al. 2005, Gfeller, Turner et al. 2007, Galvin, Fu et al. 2008, Gfeller, Oleson et al. 2008, Galvin and Fu 2011).

The majority of studies have shown that most CI users can perceive rhythm very well (Gfeller and Lansing 1991, Fujita and Ito 1999, Gfeller, Turner et al. 2002 , Kong, Cruz et al. 2004). Sometimes the rhythmic pattern of common tunes is distinctive enough to enable their identification without any melodic pitch information being available acoustically. In contrast, when melodies were presented to most CI users without rhythmic cues or lyrics, it was hard for them to recognise the melodies whereas NH people can still recognise them without these cues (Gfeller, Turner et al. 2002). It is known that pitch perception plays the main role in the recognition of melodies in such situations. It was clear that pitch was poorly perceived in most CI users when testing melodies with lyrics and rhythm removed (Fujita and Ito 1999, Kong, Cruz et al. 2004, Gfeller, Olszewski et al. 2005). Studies on timbre recognition have shown that timbre recognition in CI users is better than chance but not nearly as good as for NH listeners (Gfeller, Mehr et al. 2002, Gfeller, Witt et al. 2002). Timbre is encoded via the temporal envelope (onset characteristics in particular) and by spectral distribution of the harmonic frequencies of sound (fine structure). Temporal envelopes are fairly well preserved in CI processing, but fine structure is reduced relative to the original acoustic signal (Kong, Mullangi et al. 2012). It is likely that poor spectral coding of a musical sound is one of the responsible factors for poor pitch perception in CI users (Heng, Cantarero et al. 2011).

It is believed that current sound processing strategies which have been designed primarily for the perception of speech cannot code musical elements effectively. Therefore research has been directed to find strategies which may preserve the fine spectral structure of musical signals and improve spectral resolution in CI users. In studies of music perception on CI users a wide variation of performance is reported. This means that there are a few people whose performance in musical tests is much better than the majority of CI recipients. These people are sometimes called "star performers". The presence of star performers does not change the fact that most CI users have difficulty with music perception and appreciation, but they do demonstrate that good music perception is possible with current sound processing strategies. For example, one star performer (SP) was studied with a battery of musical tests (Maarefvand, Marozeau et al. 2013). The test battery included pitch perception, melody and timbre recognition, relative pitch, pitch magnitude estimation and consonance rating. Her results showed that her pitch perception in most experiments was comparable with NH listeners. SP could discriminate a 1 semitone difference in pitch. Her melody recognition was consistent with her pitch perception ability (near 100% score). Although her instrument recognition was not as good as for NH listeners, it was much better than the average for CI users. Consonance rating was used to test SP's perceptual judgment about different musical note intervals. A musical interval is described as consonant if it sounds harmonious and restful, while an interval is described as dissonant if it sounds discordant and tense. The ability to recognise consonance deteriorates as a consequence of cochlear hearing loss. SP found the intervals less consonant on average than the normally hearing participants, but the pattern of consonance rating across the intervals was similar for SP and the normally hearing participants with musical training.

In investigating the reasons for SP's extraordinary performance, several factors were identified. She had a long history of music training before her hearing loss (17 years of playing piano). She also continued playing piano after losing her hearing suddenly at age 27 and receiving bilateral CIs 2 years later. SP's performance with one CI in most of the experiments was not different from her results with bilateral CIs. It is possibly important that the music used for the testing was piano music, rather than being polyphonic or played on an instrument which she did not have experience with that.

Most of the experiments in this study showed that SP's performance on musical tasks was within the range of normally-hearing listeners' performance. Her results proved that a sound processing strategy designed to improve speech perception can also provide some cues via the processor which can be used in music perception, given sufficient experience of relevant musical sound. This might stem from a place pitch representation that was adequate for the perception of pitch and changes in pitch over time. The result showed that the current sound processing strategy was able to provide enough cues to subjects like SP who have had a long period of familiarization. Therefore, it is not impossible for cochlear implant users to attain enough elements of music using current speech processing schemes to recognise simple melodies. A further weakness of current sound processing strategies is revealed when factors besides pitch cues are needed, for instance fine temporal cues for timbre recognition. It is probable that improved place and temporal coding will reduce the training time required for CI recipients to achieve music perception capabilities similar to SP.

In recent years, the criteria for cochlear implantation have been relaxed, and people with more substantial residual hearing have been receiving CIs. In one configuration (bimodal CI), a CI is used in one ear and a HA in the opposite ear. Clearly bimodal listeners may hear pitch information in one or both ears. Bimodal CI users who cannot use pitch information from the implanted ear may perceive it using residual hearing in the non-implanted ear (McDermott 2011). Although bimodal CI users have been reported to have better music perception in some studies than bilateral or unilateral CI users (El Fata, James et al. 2009, Cullington and Zeng 2011) their music perception is still far from an acceptable level. In Chapters 3 and 4 of this thesis, the design and results of experiments to investigate and compare pitch perception of acoustic and electric stimuli were described to help understand music perception of bimodal listeners.

One of the fundamental principles underlying the success of cochlear implants is the tonotopic arrangement of surviving neurons in the cochlea, which produce different pitch sensations when electrodes are stimulated at different positions. This tonotopic arrangement in normally-hearing listeners is described by Greenwood's function which allows for variation in the length of the basilar membrane (Greenwood 1990). In the experiments described here, the matched pitches for single electrode and pure tone stimuli supported the notion of tonotopic place pitch perception. More basal stimulation produced higher pitch matches than more apical stimulation. There were significant individual differences between participants in the perceived pitch for fixed electrode numbers and fixed frequency tones. These differences are thought to be stemmed from some personal differences among the participants like the different length cochleae and different depths of insertion of the electrode array. Many of the matched pitches were within the general range expected from Greenwood's function, but it is likely that the predicted frequencies are too high, as found in previous studies that included individual data for depth of insertion. The consequence of this is that bimodal CI users listening to music will hear different pitches in the two ears, with the difference varying from one individual to another, and from one electrode to another.

Previous studies have suggested that other aspects of sound may affect the perception of pitch by CI users. Two of these aspects are the intensity (loudness) and type (quality or timbre) of sound. The main hypothesis of this thesis was that frequency matching in bimodal CI users would reveal the dependency of pitch perception on the type and intensity of sounds.

In NH listeners, the effect of loudness of sound on pitch perception was reported small. Several studies in CI users have shown that they perceived different pitches for soft sounds versus loud sounds (Shannon 1983, Townshend, Cotter et al. 1987, Pijl 1997, Arnoldner, Riss et al. 2008, Carlyon, Lynch et al. 2010, Green, Faulkner et al. 2012). Earlier studies concluded that this may not be a sensory effect and that it might be a bias in pitch perception (Shannon 1983, Townshend, Cotter et al. 1987, Pijl 1997, Arnoldner, Riss et al. 2008). However, recent studies which controlled the possibility of biases showed that the effect of intensity was genuine (Carlyon, Lynch et al. 2010, Green, Faulkner et al. 2012).

One common observation among these studies was that for some people the perceived pitches for loud sounds were higher, and for others they were lower (Carlyon, Lynch et al. 2010, Green, Faulkner et al. 2012). Even in NH listeners a small effect of loudness on pitch has been reported (Verschuure and Meeteren 1975). The current study has shown that in some CI users, a change in loudness of a sound can change its pitch by over an octave. If this is true, it means that pitch cannot be perceived well until the effect of loudness is controlled or compensated for. The effect of loudness is particularly important in bimodal CI users since, due to different dynamic ranges, the same sound can be perceived with different loudness in the implanted and non-implanted ears. If loudness can influence pitch, pitch may also be changing differently in the two ears, and the result can be contradictory or conflicting perceptions of pitch in two ears.

Three mechanisms relevant to the effect of loudness on pitch perception were hypothesized: Current spreading, electrode activation spreading and spectral spreading. Their effects were demonstrated in Chapter 4 using Reference stimuli that differed in the types of spreading that were relevant. It was shown that the effects of spreading were different in different participants, possibly due to the effects of patchy neural survival along the length of the cochlea. In order to reduce current spreading, modiolus-hugging electrodes have been developed (Parkinson, Arcaroli et al. 2002), current steering and focused stimulation are under development (Bonham and Litvak 2008, Bierer 2010) . The Contour electrode used in the present study already include the benefits of modiolus-hugging electrodes but current steering and focused stimulation may produce improved results. These methods may reduce the extent of current spreading, but are unlikely to compensate fully for the effects of patchy neural survival. Electrode activation spreading may occur as a result of overlapping analysis filters in the sound processor (Clark 2003, Wilson and Dorman 2008). If this is the case, this could be avoided by using non-overlapping filters, but at the cost of sound quality when smoothly changing frequency transitions such as formant transitions would jump abruptly from one electrode to another. A larger number of more closely spaced electrodes with narrow analysis filters would reduce the size and salience of these jumps. An array with more closer-spaced electrodes may also help to provide fine spectral structure that might help to resolve the harmonic structure of complex sounds provided that they stimulate independent neural populations. If the first few harmonics were resolved, then pitch perception for musical notes would probably be improved (Wilson and Dorman 2008). The idea of increasing the number of filters would be helpful provided that the spread of activation is controlled (Crew, Galvin et al. 2012).

Other developments that may improve pitch perception in future CI users include the use of neurotrophins to restore neuron loss after surgery (Gillespie, Clark et al. 2003, Landry, Fallon et al. 2013), and the development of improved surgical techniques to restore damaging surviving hair cells and neurons in the implanted cochlea. If these developments help to regenerate new neurons around patchy neural population, then the effects of current spreading may be more symmetrical around the electrodes and large pitch changes may likely be avoided with existing electrode arrays and sound processors.

Loudness is not the only aspect of sound which can change the perception of pitch. Even in NH listeners it has been reported that sound quality can change the perception of pitch to some degree. These effects were seen in the pitch matching experiments conducted for this thesis. Pure tones elicited clearer pitch percepts than piano notes in the CI ear, as shown by the higher similarity ratings and the greater range of pitch percepts in experiment B-1 compared with experiment C-1. Similarly, pure tones elicited stronger pitch percepts than complex tones in the HA ear, as shown by the higher similarity ratings and the greater range of pitch percepts in experiment B-1 compared with experiment B-2. As a result of the place pitch perception mechanisms in the implanted ear, the effects of Reference Type are related to the current spreading, electrode activation spreading, and spectral spreading discussed in this thesis. In the non-implanted ear, finer structure can often be perceived using temporal pitch perception mechanisms and the tuning curves of neurons that are narrower than the analysis filters of a cochlear implant sound processor (Limb and Roy 2014).

Although the participants in these experiments could track the changes of pitch better with pure tones than complex tones, in real life complex tones are the type of sound most commonly heard in music.

In the light of the new results presented in this thesis, it is not surprising that other authors have found that CI users can recognise musical pieces more easily when they have distinctive rhythms, when they include lyrics, when they are played by a single instrument with which the listener is familiar rather than by a band or orchestra, and when they have residual hearing.

Conclusions

1. The frequency of an Adjustable acoustic sound that matched the pitch of a Reference sound heard via a cochlear implant depended on:
    a. The Frequency of the Reference sound
    b. The Type of Reference sound
    c. The Intensity of the Reference sound
    d. The Type of Adjustable sound.
2. There were large individual differences between Participants that were likely due to:
    a. Differences in electrode array insertion depth
    b. Differences in length of the cochlea
    c. Differences in the patterns of neural damage and survival along the cochlea.
3. A typical bimodal patient listening to music is likely to experience:
    a. Different pitches in the implanted and non-implanted ears
    b. More salient pitch percepts in the non-implanted ear
    c. Greater change in pitch with intensity in the implanted ear

Future directions

The mechanisms suggested for the effects of loudness on the perception of pitch are not fully understood and require further research. For example greater exploration of sound quality of the electric-mediated sounds might be informative. Only two types of the adjustable sounds were used. It is suggested to have more diversity of sounds in the non-implanted ears to be matched with the sounds in the implanted ears.

Changes to cochlear implant sound processing should also be explored. Changes that may improve pitch perception include:

- A larger number of electrodes with narrower analysis filters in the sound processor to provide the possibility of better fine structure information provided that channel interaction is controlled
- Current steering to provide narrower current distributions around each electrode
- Use of neurotrophins to populate patchy neural survival patterns along the cochlea

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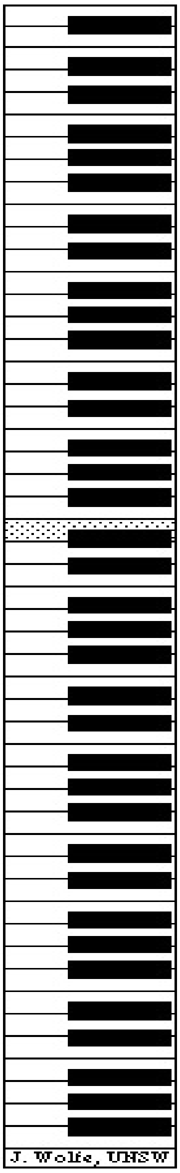
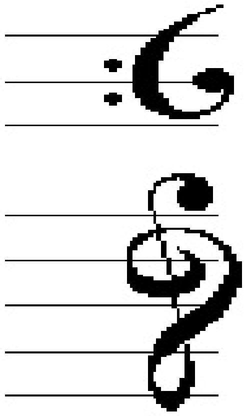
Appendices

MIDI number to Hz Table

MIDI number	Note name	Frequency Hz	Period ms
21	A0	27.500	36.36
22		29.135	34.32
23	B0	30.868	32.40
24	C1	32.703	30.58
25		34.648	28.86
26	D1	36.708	27.24
27		38.891	25.71
28	E1	41.203	24.27
29	F1	43.654	22.91
30		46.249	21.62
31	G1	48.999	20.41
32		51.913	19.26
33	A1	55.000	18.18
34		58.270	17.16
35	B1	61.735	16.20
36	C2	65.406	15.29
37		69.296	14.29
38	D2	73.416	13.62
39		77.782	12.86
40	E2	82.407	12.13
41	F2	87.307	11.45
42		92.499	10.81
43	G2	97.999	10.20
44		103.83	9.631
45	A2	110.00	9.091
46		116.54	8.581
47	B2	123.47	8.099
48	C3	130.81	7.645
49		138.59	7.216
50	D3	146.83	6.811
51		155.56	6.428
52	E3	164.81	6.068
53	F3	174.61	5.727
54		185.00	5.405
55	G3	196.00	5.102
56		207.65	4.816
57	A3	220.00	4.545
58		233.08	4.290
59	B3	246.94	4.050
60	**C4**	**261.63**	**3.822**
61		277.18	3.608
62	D4	293.67	3.405
63		311.13	3.214
64	E4	329.63	3.034
65	F4	349.23	2.863
66		369.99	2.703
67	G4	392.00	2.551
68		415.30	2.408
69	**A4**	**440.00**	**2.273**
70		466.16	2.145
71	B4	493.88	2.025
72	C5	523.25	1.910
73		554.37	1.804
74	D5	587.33	1.703
75		622.25	1.607
76	E5	659.26	1.517
77	F5	698.46	1.432
78		739.99	1.351
79	G5	783.99	1.276
80		830.61	1.204
81	A5	880.00	1.136
82		932.33	1.073
83	B5	987.77	1.012
84	C6	1046.5	0.9556
85		1108.7	0.9020
86	D6	1174.7	0.8513
87		1244.5	0.8034
88	E6	1318.5	0.7584
89	F6	1396.9	0.7159
90		1480.0	0.6757
91	G6	1568.0	0.6378
92		1661.2	0.6020
93	A6	1760.0	0.5682
94		1864.7	0.5363
95	B6	1975.5	0.5062
96	C7	2093.0	0.4778
97		2217.5	0.4510
98	D7	2349.3	0.4257
99		2489.0	0.4018
100	E7	2637.0	0.3792
101	F7	2793.0	0.3580
102		2960.0	0.3378
103	G7	3136.0	0.3189
104		3322.4	0.3010
105	A7	3520.0	0.2841
106		3729.3	0.2681
107	B7	3951.1	0.2531
108	C8	4186.0	0.2389

Keyboard





Appendix 1: table of MIDI number, note name, frequency and period of different musical sound (Wolfe 2014)

Case study paper