CURRENT STEERING WITH SEQUENTIAL STIMULATION IN COCHLEAR IMPLANTS

by

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SUMMARY

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Keywords: Current steering, sequential stimulation, place pitch, centroid, current distribution model, pitch ranking.

Current steering has been proposed to increase place pitch resolution in cochlear implant (CI) users. Many studies have shown that a current steering effect can be achieved when simultaneous stimulation is used (Koch, Downing, Osberger, Litvak and Greco, 2007, Saoji and Litvak, 2010, Wu and Luo, 2013). Some literature has shown that a current steering effect can also be achieved when sequential stimulation is used (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). Literature proposes different features that could underlie place pitch and consequently possibly also current steering effects (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008, Frijns, Kalkman, Vanpoucke, Bongers and Briaire, 2009, Macherey and Carlyon, 2012, Venter, 2015).

The present study confirmed that a current steering effect can be achieved when sequential stimulation is used by using multi-dimensional scaling and statistical analysis in addition to the convention of using cumulative d' values to analyse pitch ranking results of current steering experiments. It was however observed that a current steering effect could only be

achieved in listeners who were at least able to pitch rank the pitch of the two individual stimulating electrodes correctly according to expectation.

The effect of different stimulation parameters on the pitch ranking ability of CI users during current steering experiments was investigated. Results showed that some parameters only had an effect on the pitch ranking performance of some listeners, while other stimulation parameters affected the results of all the listeners. Wider stimulation pulse widths, for example, led to improved pitch ranking results for some listeners. Most listeners benefited from wider electrode separation distances. Statistical analysis showed that there was a significant improvement in the pitch ranking performance of the listeners during experiments where the stimulation rate was the same as the rate indicated on the clinical MAP of the listener.

Person-specific current distribution models were used to predict the cochlear position of different stimuli because of different features that could underlie place pitch, for each of the experiments for four of the listeners who participated in this study. The model predictions were related to the measured pitch ranking results using correlation and mutual information analysis. The results indicated that the current centroid at electrode level, the position of the peak current at the auditory nerve level (because of either an individual stimulating electrode or because of summed currents) and the centroid of neural activation could underlie place pitch. All these features except the position of the peak of the current distribution at the auditory nerve level because of each individual stimulating electrode could underlie current steering effects. Results showed that the centroid of the current distribution at the auditory nerve level probably does not underlie place pitch.

Knowledge about the impact that different stimulation parameters have on the ability to achieve a current steering effect could result in more efficient implementation of current steering effects. Proper knowledge of which features underlie place pitch and current steering effects could be used to create models that can be used to predict the results of place pitch experiments.

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OPSOMMING

STROOMSTUUR MET OPEENVOLGENDE STIMULASIE IN KOGLEÊRE INPLANTINGS

deur

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Sleutelwoorde: Stroomstuur, opeenvolgende stimulasie, plek-toonhoogte, sentroïed, stroomverspreidingmodel, toonhoogteplasing.

Stroomstuur is voorgestel om plek-toonhoogteresolusie in gebruikers van kogleêre inplantings (KI) te verbeter. Baie studies het getoon dat ’n stroomstuur-effek verkry kan word as gelyktydige stimulasie gebruik word (Koch *et al*., 2007, Saoji and Litvak, 2010, Wu and Luo, 2013). Van die literatuur het getoon dat ’n stroomstuur-effek ook bereik kan word as opeenvolgende stimulasie gebruik word (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). Die literatuur verwys na verskillende verskynsels wat moontlik die grondslag is van plek-toonhoogte en gevolglik moontlik ook van stroomstuur-effekte (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008, Frijns *et al*., 2009, Macherey and Carlyon, 2012, Venter, 2015).

Die huidige studie het bevestig dat ’n stroomstuur-effek bereik kan word wanneer opeenvolgende stimulasie gebruik word deur die aanwending van multi-dimensionele skalering en statistiese analise bykomend tot die konvensie om kummulatiewe d'-waardes te gebruik om toonhoogteplasingresultate van stroomstuur-eksperimente te analiseer. Daar is nietemin waargeneem dat ’n stroomstuur-effek net bereik kon word in luisteraars wat minstens in staat was om die toonhoogte van die twee individuele stimulasie-elektrodes korrek te plaas volgens verwagting.

Die effek van verskillende stimulasieparameters op die toonhoogteplasing-vermoë van KI-gebruikers tydens stroomstuur-eksperimente is ondersoek. Die resultate het getoon dat van die parameters net ’n uitwerking op die toonhoogteplasingprestasie van sommige luisteraars gehad het, terwyl ander stimulasieparameters die resultate van al die luisteraars beïnvloed het. Wyer stimulasie-pulswydtes het byvoorbeeld gelei tot verbeterde toonhoogteplasingresultate vir sommige luisteraars. Die meeste luisteraars het baat gevind by wyer elektrode-skeidingafstande. Statistiese analise het ’n beduidende verbetering in the toonhoogteplasingprestasie van die luisteraars getoon tydens eksperimente waar die stimulasietempo dieselfde was as die tempo wat op die kliniese MAP van die luisteraar aangedui is.

Persoon-spesifieke stroomverspreidingmodelle is gebruik om die kogleêre posisies van verskillende stimuli te voorspel omdat verskillende eienskappe die onderbou vir plek-toonhoogte mag vorm, vir elk van die eksperimente vir die vier luisteraars wat aan die studie deelgeneem het. Die modelvoorspellings is in verband gebring met die gemete toonhoogteplasing-resultate deur die gebruik van korrelasie en wedersydse informasie-analise. Die resultate het getoon dat die stroomsentroïed op elektrodevlak, die posisie van die piekstroom op die gehoorsenuweevlak (omrede óf individuele stimulasie-elektrodes óf totale stroom) en die sentroïed van neurale aktivering die grondslag van plek-toonhoogte mag wees. Al hierdie kenmerke, behalwe die posisie van die piek van die stroomverspreiding op die gehoorsenuweevlak danksy elke individuele stimulasie-elektrode, kan die grondslag van stroomstuur-effekte wees. Die resultate het getoon dat die sentroïed van die stroomverspreiding op die gehoorsenuweevlak waarskynlik nie die grondslag van plek-toonhoogte is nie.

Kennis van die impak van verskillende stimulasieparameters op die vermoë om ’n stroomstuur-effek te bereik kan meer doeltreffende implementering van stroomstuur-effekte tot gevolg hê. Voldoende kennis oor watter kenmerke die grondslag vorm van plek-toonhoogte en stroomstuur-effekte kan gebruik word om modelle te skep wat gebruik kan word om die uitkomste van plek-toonhoogte-eksperimente te voorspel.

LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
ANSI	American national standards institute
C-FITA	Continuous FITA
CI	Cochlear implant
CT	Computerised tomography
CU	Current unit
FITA	Feature information transmission analysis
GUI	Graphical user interface
MDS	Multi-dimensional scaling
MI	Mutual information
PC	Personal computer
PRDL	Pulse rate difference limen
R-FITA	Ranking FITA
SNR	Signal-to-noise ratio

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

1.1.1 Context of the problem

For many years, cochlear implants (CIs) have been used to restore the hearing of severely to profoundly deaf people (Loizou, 1999, Clark, 2003). Though effective, CIs do not provide normal hearing (Grifford and Revir, 2010). The spectral resolution of current CI speech processing is limited by the number of implanted electrodes as well as the speech processing strategies. Because of the limited spectral resolution of CI systems, the lower harmonics of speech that give normal listeners spectral cues to pitch are not resolved (Green, Faulkner and Rosen, 2002). A primary consequence of the limited spectral resolution is the loss of pitch perception in CI listeners (Gantz, Turner, Gfeller and Lowder, 2005). It has been stated that pitch perception is key for good speech perception and accurate perception and appreciation of music (Green *et al*., 2002, Gantz *et al*., 2005, Turgeon, Champoux, Lepore and Ellemberg, 2015).

Pitch perception is based on two fundamental mechanisms (Hartmann, 1996, McDermott, 2004). The first is referred to as rate pitch and the second is called place pitch. The ability to extract rate pitch depends on rapid temporal fluctuations in electric stimuli. CI users generally have good temporal resolution (Hanekom and Shannon, 1998). Studies have shown that there is a relationship between the stimulation pulse rate and the perceived pitch (Pijl, 1995, Pijl and Schwarz, 1995a, Pijl and Schwarz, 1995b, Blamey, Dooley, Parisi and Clark, 1996, McDermott and McKay, 1997). Many studies have however found that CI users cannot distinguish between different pitches based on rate pitch cues when the stimulation rate is higher than 300 pps (Shannon, 1983, Tong, Clark and Lim, 1987, Townshend, Cotter, Van Compernolle and White, 1987, McDermott and McKay, 1997, McKay, McDermott and Carlyon, 2000, Zeng, 2002).

The place pitch mechanism relies on the location in the cochlea at which the electric stimulus is delivered. The intention is that different stimulating electrodes would stimulate different neural populations. A place pitch is created at the place of maximum neural excitation. Stimulation of the more basal electrodes will probably create a sound that is perceived as higher in pitch, while stimulation of the more apical electrodes will probably create a sound that is perceived as lower in pitch (Nelson, Van Tasell, Schroder, Soli and Levine, 1995, Baumann and Nobbe, 2004).

Current steering has been proposed as a method to improve place pitch perception. Specifically, current steering can potentially create intermediate place pitches between adjacent electrodes, providing increased spatial resolution (Kwon and van den Honert, 2006). Usually, to create a current steering effect, current is delivered simultaneously to adjacent electrodes. By varying the proportions of current delivered to each electrode, the current is steered to create intermediate pitches between the two stimulating electrodes (Firszt, Koch, Downing and Litvak, 2007). Notably, some research has shown that intermediate place pitch percepts could also be created by sequential stimulation of nearby electrodes (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008).

Many studies propose that place pitch is related to a centroid in activation caused by the stimulation pattern (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008, Frijns *et al.*, 2009, Macherey and Carlyon, 2012, Venter, 2015). "Activation" in this sentence is deliberately vague. What may be confusing is that each of the studies refers to a different centroid. Some state that the centroid of the neural activation pattern can predict pitch (McDermott and McKay, 1994, Frijns *et al.*, 2009). Other studies refer to the centroid of the current or potential distribution close to the basilar membrane (Macherey and Carlyon, 2012). There have also been studies that use the centroid of the current distribution along and close to the electrode array as a predictor of place pitch (McDermott and McKay, 1994, Laneau, Wouters and Moonen, 2004).

1.1.2 Research gap

Research gap 1. Although current steering is usually considered in the context of simultaneous stimulation on different electrodes, some studies have shown that it is possible to achieve a current steering effect using sequential stimulation (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). To cater for the wider population of CI users it is important to confirm the findings of the cited studies, because some speech processors can only stimulate sequentially and cannot stimulate simultaneously.

Research gap 2. Each of these cited studies only tested a few listeners and used cumulative d'[1] values to determine if the listeners could distinguish between different pitches presented during a pitch ranking task. The sensitivity index can only be used to determine the perceptual distance in pitch between two stimuli; it cannot be used to rank multiple stimuli in a pitch rank order. Another factor to be considered is that d' can only be used to determine the perceptual distance between two pitches under the assumption that pitch perception is unidimensional. Section 3.2.3 elaborates on this statement. The possibility that pitch perception of stimuli, created using current steering and monopolar stimulation, are multi-dimensional was not considered in the studies cited above.

There might be more comprehensive methods than the calculation of d' values to analyse pitch ranking results of stimuli created using current steering. These methods should typically consider a factor such as the possibility that the results of pitch perception may be multi-dimensional. It should also consider that pitch rank orders must be determined without any initial assumptions such as the way a pitch rank order is often assumed when d' values are calculated. Additional to calculating d' values, multi-dimensional scaling (MDS) was used in this study to determine pitch rank orders. Using another technique, such as MDS, to determine the pitch rank of stimuli created by using current steering could support or perhaps refute the findings of the cited studies. This topic could be viewed as a possible shortfall in the method popularly used to analyse pitch ranking results, rather than a research gap.

[1] d' is pronounced d prime.

Research gap 3. A variety of stimulation parameters were used between three studies that tested the possibility of creating a current steering effect using sequential stimulation: stimulation mode (monopolar or bipolar), phase width, inter-pulse delay, stimulation rate, electrode separation distance and time between pulses on the adjacent electrodes (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). The stimulation parameters mentioned above are shown in Figure 1.1 for clarity.

The effects of the different stimulation parameters on the pitch ranking ability of CI listeners, presented with stimuli created using current steering effects with sequential stimulation, are not clear from the cited studies. Using different stimulation parameters in each study, each of the studies showed that current steering effects could be achieved. It is possible that certain stimulation parameters might make it easier for the CI listener to perform well in a pitch ranking experiment, where the stimuli are created with the aim to achieve current steering effects by using sequential stimulation. In the present study, a number of psychoacoustic experiments, with a variety of stimulation parameters, were carried out with each CI listener to determine the effect of different stimulation parameters on their pitch ranking ability when stimuli were created with the aim to achieve a current steering effect by using sequential stimulation.

Research gap 4. Current steering is potentially a way to manipulate place pitch. A study has shown that the pitch of the sounds used was probably determined by a centroid-related parameter (Laneau *et al*., 2004). Current steering studies (both for sequential and simultaneous stimulation) have also stated that the pitch of the stimuli used is determined by a centroid-related parameter (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). As mentioned earlier, different publications refer to different centroids (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008, Frijns *et al*., 2009, Macherey and Carlyon, 2012, Venter, 2015). Section 4.2.2 describes these different centroids. There may be a feature other than centroids that encodes place pitch, for example the place of maximum applied current. Comparing model predictions with experimental data may clarify which of the different centroids describes place pitch data best. If some of the modelled predictions closely represent the experimental data, it may be assumed that the modelled features that lead to the specific modelled prediction may underlie place pitch. Studies that compare the different features that possibly underlie place pitch with measured data do not appear to be available at present.

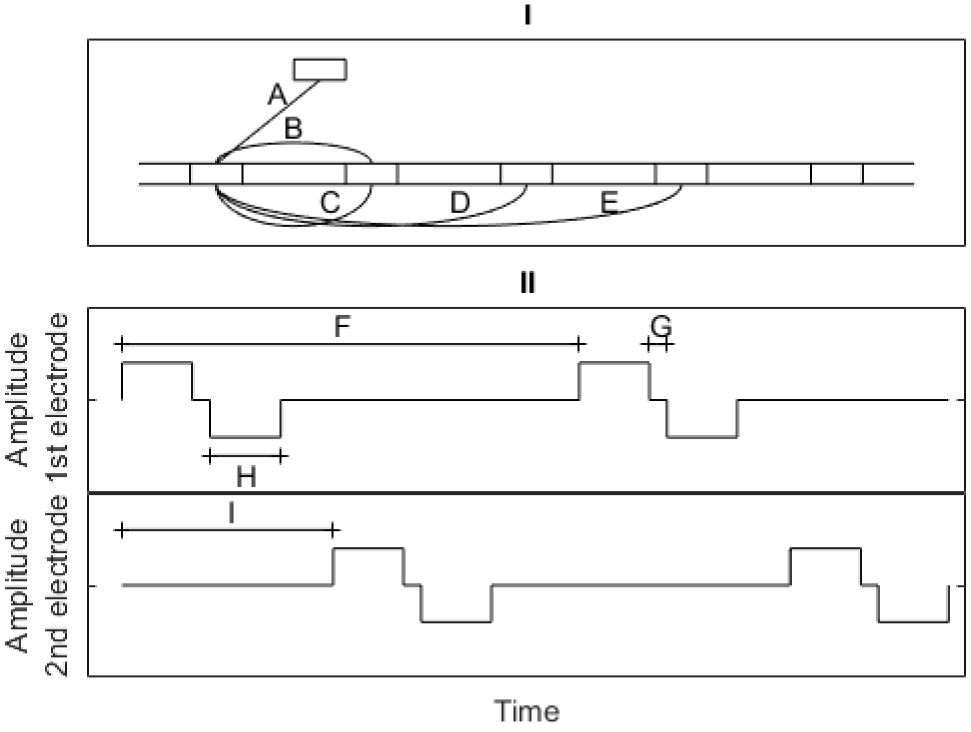


Figure 1.1 Visual explanation of different stimulation parameters. Panel I shows the intra-cochlear electrode array and the reference electrode. During stimulation, current flows from an active electrode to a reference electrode. During monopolar stimulation, current is passed between one active intra-cochlear electrode and the extra-cochlear reference electrode. This is shown by A. During bipolar stimulation, both the active and the reference electrodes are within the cochlea. This is shown by B. C, D and E show electrode separation distances of 1, 2 and 3 respectively. Panel II shows the current waveform on each of two sequentially stimulating electrodes over time. The reciprocal of the stimulation rate, i.e. the stimulation period, is shown by F. G, H and I show the inter-pulse delay, phase width and time between pulses on the adjacent electrodes respectively.

1.2 OBJECTIVES AND RESEARCH QUESTIONS

Four specific objectives were pursued during this study. The first objective of the study was to confirm that it is possible to create a current steering effect using sequential stimulation. This aspect of the study included the use of MDS to analyse pitch ranking results. The second objective was to determine if a certain set of stimulation parameters would deliver better pitch ranking results than others in CI users when current steering effects are used to create stimuli.

The third objective was to reconsider the often-used methodology of using d' values to express perceptual distance between stimuli, and to use MDS to express perceptual distance between stimuli and to determine pitch ranks.

The fourth objective was to use person-specific models (Malherbe, Hanekom and Hanekom, 2015) along with the measured data to determine which physical representation underlies place pitch. The present study investigated different features resulting from electrical stimulation that may underlie place pitch. The fourth objective was thus to determine which of the proposed centroid-related features or which of the features related to the place of maximum applied current most probably underlies place pitch.

For brevity, the terminology "features resulting from electrical stimulation" will be abbreviated simply as "features" in the text that follows. Where confusion is possible, the complete term is used. The usage of "features" follows Oosthuizen (2017), who indicated that while there is overlap in the meanings of the terms "cue" and "feature", "feature" is preferred because "cue" implies that there is a strong reliance on that particular feature for a listening task, while "feature" describes a physical characteristic of the signal that may or may not be important in the listening task.

The following research questions were investigated.

- Is it possible to achieve a current steering effect using sequential stimulation? This question has been investigated to some extent in a few other studies, cited earlier. In the present study, the experimental design was similar to these, but the experimental results were analysed using different techniques.
- Do stimulation parameters determine pitch ranking ability when sequential stimulation is used to steer current? Are there more effective and less effective choices for stimulation parameters?
- Is place pitch predicted by centroid-related features, by features related to the place of maximum applied current, or neither or these?
- Which of the different centroids mentioned in literature corresponds best with place pitch?

1.3 APPROACH

Pitch ranking experiments were carried out to confirm whether a current steering effect can be obtained using sequential stimulation. By varying the amount of stimulation current on each electrode, it was assumed that a specific, expected pitch rank order would be measured. The assumption was that it would be confirmed that a current steering effect could be obtained if the CI listener could correctly order the pitches of the sounds to match the expected pitch order. Pitch ranking experiments were conducted with CI listeners in a series of experiments, with each experiment using different stimulation parameters. The pitch ranking results were documented and analysed using MDS. The results were used to confirm the findings of the previous current steering studies, which also used sequential stimulation. The results of the different experiments were compared to determine the effects of the different stimulation parameters.

There are a number of different schools of thought in the literature as to what physical features underlie place pitch perception. In this study, some of the experimental results were compared to a person-specific current distribution model to determine which of these hypotheses best explains the experimental data. A person-specific current distribution model was constructed using data obtained from a person-specific, finite element model (Malherbe *et al*., 2015). The finite element models were constructed using computerised tomography (CT) scans of three CI users who participated in the present study as well.

Each person-specific current distribution model consisted of a rolled-out cochlea, including both the electrode array and the auditory nerve. Current distributions in the space between the electrode array and the auditory nerve were calculated using current distribution predictions obtained from the finite element models. The specifics of the modelling process are discussed in more detail in Section 4.2. These person-specific models were used to calculate the different centroids mentioned, for each of the different stimuli used in the experiments. These predictions were related to the results obtained through the experiments.

1.4 RESEARCH CONTRIBUTION

The present study investigated the effect of different stimulation parameters on the ability of CI listeners to perform a pitch ranking task, where the stimuli were created with the aim to create current steering effects with sequential stimulation. More effective and less effective choices for stimulation parameters were found and are discussed in Section 3.4.2. Implementing stimulation parameters at which a current steering effect can improve the pitch ranking ability of CI listeners can lead to more effective speech-processing strategies, allowing for larger pitch resolution and in turn improved pitch perception.

The different centroids and features mentioned in literature, which might underlie place pitch, were modelled and related to measured data. The present study indicates which features are more probable and less probable to underlie place pitch.

1.5 RESEARCH OUTPUTS

The following article is in preparation.

Roux, J. and Hanekom, J. J. Place pitch with sequential current-steered stimuli in cochlear implants, To be submitted to *Journal of the Acoustical Society of America*.

1.6 OVERVIEW OF STUDY

Chapter 2 discusses the motivation for the research in broader detail. The chapter explores current literature on place pitch, current steering and models that are used to predict place pitch. Chapter 3 investigates and discusses the viability of current steering though sequential stimulation. The effect of different stimulation parameters on current steering, carried out using sequential stimulation, is also presented in this chapter. Chapter 4 compares the experimental results with model predictions to assess the influence of different features proposed by literature for place pitch encoding. Chapter 5 concludes the study by highlighting the important findings, discussing possible implications of the findings and by providing suggestions for future work.

CHAPTER 2 LITERATURE STUDY

2.1 INTRODUCTION

The previous chapter gave some insight into the context of the problem that was addressed in the present study. It also explained the research gap and the research objectives of the present study. This chapter will elaborate on the literature foundation for the present work. Topics include different mechanisms by which pitch is encoded and possible methods of increasing the number of audible pitches in a specific pitch range.

As a general statement, CIs can restore the hearing of severely to profoundly deaf people to some extent, which would differ between CI users (Loizou, 1999, Clark, 2003). Over the past few decades, CIs have enabled routine achievement of language perception in many, but not all, users (Loizou, 1999, Clark, 2003). Even though CIs have successfully restored some hearing of severely to profoundly deaf people, they do not provide normal hearing (Grifford and Revir, 2010). Listeners with CIs require a much more favourable signal-to-noise ratio (SNR) than normal hearing listeners to obtain the same degree of success with speech recognition under noisy conditions (Grifford and Revir, 2010). Among many different reasons for this, poor pitch perception of CI users has been highlighted as an important contributor (Gantz *et al*., 2005). Better access to pitch information would be expected to increase speech perception (Green *et al*., 2002).

2.2 PITCH AND TIMBRE

While frequency is a physical attribute of the waveforms of a sound, measured in Hertz, pitch is a perceptual attribute of a sound. Pitch refers to the sensation the sound produces in a listener, which allows the listener to order sounds on a frequency scale from high to low or low to high.

The definition often used by psychoacousticians for pitch is “that attribute of auditory sensation in terms of which sound may be ordered on a musical scale” (ASA, 1960, Plack and Oxenham, 2005, Swanson, 2008). It has been explained that this does not mean that pitch is restricted to musical sounds (Hartmann, 1996). It means that the psychological dimension implied by the term “pitch” and the psychological dimension of a musical melody are the same (Hartmann, 1996).

A particular study has defined pitch as the auditory percept related to the repetition rate of periodic sounds (Oxenham, Micheyl, Keebler, Loper and Santurette, 2011). The formal American National Standards Institute (ANSI) definition states that “Pitch [is] that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high; pitch depends primarily on the frequency content of the sound stimulus, but it also depends on the sound pressure and the waveform of the stimulus” (ANSI, 1994). This definition includes effects such as the increase in the brightness of a sound as the level of its high-frequency content increases (Plack and Oxenham, 2005). The brightness of a sound is a property of sound timbre. Consequently, the ANSI definition includes properties apart from those that may be regarded as purely pitch, such as timbre.

Pitch has also been defined by saying that “A sound can be said to have a certain pitch if it can be reliably matched by adjusting the frequency of a pure tone of arbitrary amplitude” (Hartmann, 1997). This definition can possibly include one, or all three of pitch, loudness and timbre (Plack and Oxenham, 2005).

Timbre is a perceptual property that distinguishes sounds of the same pitch (Lyon and Shamma, 1996). An example often used to explain timbre is different musical instruments playing the same note, for example middle C. While all the instruments are playing the same note or frequency, it can still be distinguished as coming from different musical instruments.

Studies have indicated that pitch can be determined by finding the fundamental frequency of a sound, F0 (Schubert, Wolfe and Tarnopolsky, 2004). It has also been shown that the “brightness” parameter of timbre is given by the spectral centroid of a sound (Schubert *et al.*, 2004). It is clear that timbre and pitch are two different attributes of a sound. Numerous studies, conducted on normal hearing listeners, have found that the pitch and timbre of isolated tones interact perceptually (Krumhansl and Iverson, 1992). However, experiments with normal hearing listeners showed that when a number of tones were played in longer sequences, there was no interaction between timbre and pitch (Krumhansl and Iverson, 1992). That is, when the pitch of the tones was changed during the experiments measured above, it did not affect the timbre recognition and vice versa.

It has been stated that with psychoacoustic experiments, conducted with CI users, it is nearly impossible to distinguish absolutely between changes in pitch and changes in timbre (McDermott, 2004). A study was carried out on CI listeners to compare the effect of monopolar and tripolar stimulation on complex pitch-ranking tasks. Male and female singing voices separated by either a half or a quarter octave were used during the pitch-ranking task. Some results indicated there was a possibility that participants used cues other than pitch, such as timbre, to do the pitch-ranking task (Fielden, Kluk, Boyle and McKAy, 2015). Another study analysed the relative contributions of temporal and place pitch cues to fundamental frequency discrimination in CI users (Laneau *et al*., 2004). The results of the study also raised questions with regard to whether place pitch is truly a pitch percept or whether it rather relates to the brightness aspect of the timbre of the sound.

It is important to realise that although there might be interaction on a perceptual level between rate pitch, place pitch and timbre, each of these are different attributes of a sound. In CI listeners rate or temporal pitch would most likely refer to the pitch sensation created by neural spike trains that phase lock onto a certain stimulation rate. Rate pitch is discussed in more detail in Section 2.3. Literature has shown that place pitch and timbre are often confused by both normal hearing and CI listeners. However, as mentioned before, these are two different attributes of sounds. Place pitch in CI users would perhaps rather refer to the pitch sensation created by the place of maximum stimulation current along the cochlea, while timbre would rather refer to the centroid of the current distribution along the cochlea. Place pitch is discussed in more detail in Section 2.4.

2.3 RATE PITCH

Some pitch models assume that the frequency of a tone is encoded by the timing patterns of neural pulses (Hartmann, 1996). Data, measured on cats, has shown that timing patterns that reflect the fundamental frequency or the repetition rate of a sound can be observed in the auditory nerve (Johnson, 1980, Hartmann, 1996).

Neurons of the auditory nerve fire spontaneously while acoustic stimulation is absent. Once a neuron has fired, it can only fire again after a refractory period. The neurons fire at random times and may produce rates up to 100 spikes per second. When the intensity of a tone is increased to be above threshold, neural spikes begin to order themselves in time to synchronise with the period of the signal (i.e., they phase lock to the acoustic input signal) (Hartmann, 1996).

It has been shown that CI users have good temporal perception (Hanekom and Shannon, 1998) and that there is a relation between the stimulation pulse rate and the perceived pitch (Pijl, 1995, Pijl and Schwarz, 1995a, Pijl and Schwarz, 1995b, Blamey *et al.*, 1996, McDermott and McKay, 1997). Considering these factors, it was proposed that improved pitch perception in cochlear implantees can be achieved by encoding pitch by controlling the rate at which the electrodes of CIs are stimulated (Venter, 2015). Numerous studies have stated that a fundamental limit to pulse rate discrimination exists in CIs at 300 pps (Shannon, 1983, Tong *et al.*, 1987, Townshend *et al.*, 1987, McDermott and McKay, 1997, McKay *et al.*, 2000, Zeng, 2002). This fundamental limit to pulse rate discrimination was one of the major foci of the study conducted by Venter (2015). The cited study showed that the previously observed deterioration of pulse rate difference limens (PRDLs) at 300 pps, which had been thought to reflect a fundamental limit to rate discrimination, could possibly be eliminated with the correct choice of stimulus parameter (Venter and Hanekom, 2014). This means that with the correct choice of stimulation parameters, it might be possible to provide CI listeners with a wider usable rate pitch range. Access to a wider variety of pitches may improve pitch perception in CI listeners.

2.4 PLACE PITCH

Normal hearing is enabled through the functions of the outer, middle and inner ear (Purves, Augustine, Fitzpatrick, Katz, Lamantia, McNamara and Williams, 2001). The outer ear receives acoustic pressure waves. These waves are guided by the pinna and translated into mechanical vibrations by the tympanic membrane. The tympanic membrane is attached to the three middle ear ossicles (maleus, incus and stapes). The high impedance of the perilymph (fluid in the scala vestibuli and scala tympani within the cochlea) is matched to the low impedance of air by the ossicles of the middle ear. The cochlea, situated in the inner ear, transforms the mechanical vibrations into pressure fluctuations in the endolymph. The basilar membrane, situated in the cochlea, separates the scala media and the scala tympani. Pressure fluctuations in the perilymph lead to displacement of the basilar membrane.

The basilar membrane acts as a linear dispersive filter. Displacements of the membrane capture information about the frequency content of the acoustic signal (Purves *et al*., 2001). As the acoustic waveform travels from base to apex, more and more frequency components are removed from the waveform (from high to low frequencies) (Purves *et al*., 2001). Displacement of the basilar membrane causes a shearing force that bends the stereocilia of the hair cells. As the stereocilia of the hair cells bend, neurotransmitter is released that cause neurons that innervate the hair cells to generate action potentials (or to fire). Information about the acoustic signal is communicated in this way to the auditory processing centres in the brain via the auditory nerve that exits the cochlea and carries information to the cochlear nucleus.

Measurements in human cadavers, cat, chinchilla, guinea pig, gerbil and monkey have shown how peak basilar membrane motion occurs near the cochlear apex for low-frequency tones and near the oval window for high-frequency tones (Greenwood, 1990, Hartmann, 1996). An equation that can be used to determine the place of maximum excitation along the basilar membrane as a function of the frequency of a pure tone that generates the excitation is

$$f = A(10^{ax} - k), \tag{2.1}$$

where f is the frequency, x is the distance from the apex of the cochlea and a and k are constants (Greenwood, 1990). There is an almost exponential relationship between the place of maximum excitation in the cochlea and the frequency of the input tone (Greenwood, 1990).

Present-day cochlear implants make use of place coding to encode frequency information. Multi-electrode arrays, consisting of up to 22 electrodes, are used to target different populations along the cochlea. The pitch of a sound is related to the place of stimulation in the cochlea (Kwon, Perry and Olmstead, 2011). The electrodes that stimulate nerves closer to the basal area typically result in higher perceived pitch , while stimulation of nerves closer to the apical region typically results in lower perceived pitch (Nelson *et al*., 1995, Baumann and Nobbe, 2004).

One line of work within CI design aims to create methods to stimulate largely non-overlapping populations of neurons while maximising the number of non-overlapping populations (Wilson and Dorman, 2008). In theory, increasing the number of electrodes used for stimulation may result in increased spectral resolution. It has been shown that speech intelligibility and vowel and consonant recognition improve as the number of electrodes used for stimulation increases (Friesen, Shannon, Baskent and Wang, 2001). However, studies have shown that even for CIs with 22 electrodes, CI users are not able to utilise more than 4-10 independent information channels (Friesen *et al*., 2001, Wilson and Dorman, 2008).

Poor spectral resolution in CI users is attributable to a variety of factors, among others the distance between the electrodes and the target neural structures, geometric arrangement of the electrodes, spread of neural excitation associated with electrical stimulation, electrode interaction, and anatomical factors such as nerve survival, ossification and fibrosis around the implant (Loizou, 1999, Friesen *et al*., 2001, Rubinstein, 2004, Wilson and Dorman, 2008).

As mentioned earlier, CI users generally have poor pitch perception. Poor place pitch perception in CI users is primarily a consequence of the limited spectral resolution of CIs (Gantz *et al*., 2005). Studies have shown that while CI users with poor pitch resolution can still understand speech in a quiet environment, fine spectral resolution is needed for CI users to understand speech in background noise (Fishman, Shannon and Slattery, 1997, Fu, Shannon and Wang, 1998). One of the solutions proposed for improved spectral resolution in CI users is to use current steering to create pitches intermediate to the pitches created by stimulating individually on two adjacent electrodes (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Koch *et al*., 2007, Saoji and Litvak, 2010, Wu and Luo, 2013).

2.5 PLACE PITCH MANIPULATION WITH CURRENT STEERING

Cochlear implant users may perceive intermediate place-pitches between those elicited by individually stimulating two electrodes. If intermediate place-pitches can be created, this would eliminate the spatial resolution limitations that exist owing to the fixed number of electrodes (McDermott and McKay, 1994, Kwon and van den Honert, 2006). Current steering could provide a continuously variable place-related pitch (McDermott and McKay, 1994). The intermediate place-pitches, created using current steering, reflect increased spatial resolution (Kwon and van den Honert, 2006). Current steering can be achieved using either simultaneous or sequential stimulation (Kwon and van den Honert, 2006). The following two sections elaborate on this. Not all speech processors can stimulate simultaneously, which makes it particularly important also to be able to achieve a current steering effect when sequential stimulation is used.

2.5.1 Simultaneous stimulation

Simultaneous delivery of current to adjacent electrodes, where the aim is to steer the stimulation to sites between the individual electrodes by varying the proportion of current delivered to each electrode in an electrode pair, is often referred to as current steering (Firszt *et al*., 2007). It has been proposed that current steering is possible when simultaneous stimulation is used owing to the superposition or summation of currents from different electrodes (McDermott and McKay, 1994, Kwon and van den Honert, 2006). The stimulation current distributes through the cochlea and causes an extracellular voltage potential at the auditory neurons. The neural excitation at a certain position along the auditory nerve is dependent on the intracellular and extracellular voltage potentials of the neurons at the given position (Macherey and Carlyon, 2012). Place pitch is thought to correspond to the place of maximum neural excitation and is therefore thought to correspond to the centroid of the voltage distribution along the auditory nerve (Macherey and Carlyon, 2012).

Many studies have shown that the number of pitch percepts between two adjacent electrodes can be increased through current steering (Koch *et al*., 2007, Saoji and Litvak, 2010, Wu and Luo, 2013). It has been shown in a particular study in a group of CI users that through current steering CI listeners with 16-contact arrays have an average of 93 spectral channels that can be distinguished in pitch (Koch *et al*., 2007).

Experiments have also been carried out where focused partial tri-polar mode was used for current steering (Wu and Luo, 2013). This too showed that current steering may improve spectral resolution.

Current steering is usually carried out by using adjacent electrodes. Current steering can be carried out with wider electrode separation, which is sometimes referred to as spanning (Snel-Bongers, Briaire, Vanpoucke and Frijns, 2011). Spanning experiments showed that the pitch created by a stimulus that delivers equal proportions of current to the two stimulating electrodes is the same as the pitch produced by an intermediate physical electrode (Snel-Bongers *et al*., 2011). Nevertheless, the experiments showed that with increasing electrode spanning distance there is a gradual deterioration in the just noticeable difference of pitch. The cited study also found that more current adjustment is needed to maintain equal loudness between stimuli created using greater spanning distances and stimuli created using smaller spanning distances.

2.5.2 Sequential stimulation

When sequential stimulation is used, unlike the case of simultaneous stimulation, current summation cannot occur because the stimulating electrodes do not provide current at the same time. A current steering effect created with sequential stimulation is said to be possible because of the spatial overlap of the neural excitation distribution, along with the refractory period of the neurons (McDermott and McKay, 1994). Each electrode stimulates its own population of neurons. However, spatial overlap occurs when electrodes in close proximity are stimulated. If these electrodes are stimulated within the refractory period of the neurons, it might lead to a single, broader distribution of neural excitation.

As explained in the previous section for simultaneous stimulation, it is proposed that the place pitch created in response to sequential stimulation could also be related to a centroid. The place pitch would not be expected to be related to the centroid of the voltage distribution (as was the case for simultaneous stimulation), but rather the centroid of the combined neural excitation distribution (McDermott and McKay, 1994). The centroid of the combined neural excitation distribution is expected to be located between the centroids of the neural excitation distributions of each electrode in the electrode pair when they are activated separately (McDermott and McKay, 1994).

To some extent the effects (on neural activation patterns) of current steering can be related to the effects of three adjacent stimulating electrodes. If current steering is applied to the two (of the three) electrodes with the furthest separation, it is expected that it would be possible to create a neural activation pattern that would be the same as that achieved when the physical intermediate electrode is stimulated individually.

A few studies showed that intermediate place-pitch percepts could be created by sequential stimulation of nearby electrodes (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). These studies investigated the ability of CI listeners to discriminate between the pitch of stimuli created by stimulating individually on each of the stimulating electrodes and their intermediate pitch precepts. The methods and findings of each of the studies are discussed in the following few paragraphs.

Five experienced users of the Mini System 22 participated in the study of McDermott and McKay (1994). The stimuli used during the experiments were created using constant current biphasic pulses. Bipolar (BP) +1 and BP+2 and common ground modes were used for stimulation. A stimulation period of 4 ms and a stimulation duration of 500 ms were used. The time between the pulses on the adjacent electrodes was 0.4 ms. This duration was chosen because it is probably less than the neural refractory period (Swanson, 2008). It has been stated that the time between stimulation on the adjacent electrodes should probably be smaller than the neural refractory period to ensure that there is neural interaction between neural channels (McDermott and McKay, 1994). As previously explained, it is expected that neural interaction will be necessary to achieve a current steering effect when sequential stimulation is used.

The study suggested that during sequential dual-electrode stimulation the two populations of neurons excited by each stimulating electrode overlap spatially (McDermott and McKay, 1994). It was suggested that the place pitch percept could be determined by the centroid of the combined neural excitation distribution (McDermott and McKay, 1994). The study showed that the pitch of a dual-electrode stimulus was intermediate to, and moved monotonically between the two electrodes of the electrode pair as the relative current amplitudes were gradually shifted from stimulation on the one electrode only to stimulation on the other electrode only (McDermott and McKay, 1994). BP+2 mode has an extent of 2.25 mm. Since this is the largest extent that was tested, there is no indication in this study of what would happen if the extent should be widened.

Swanson (2008) used monopolar stimuli, with 25 μs phase width and 8 μs inter-pulse delay. A stimulation period of 563.2 μs and a stimulation duration of 500 ms were used. The time between the pulses on the adjacent electrodes was 70.4 μs. Both the stimulation period and the time between the pulses on the adjacent electrodes of this study were shorter than those used by McDermott and McKay (1994). The results of this study showed that pitch percepts can be created between two adjacent electrodes if a dual-electrode stimulus using monopolar stimulation is used (Swanson, 2008).

Kwon and van den Honert (2006) conducted a similar experiment. For this experiment, biphasic, monopolar stimuli were used. A phase width of 25 μs and an 8 μs inter-pulse delay were used for this experiment. The stimulation rate was kept the same as that used in the listeners' clinical MAP. A stimulation duration of 500 ms was used. It was concluded that intermediate place pitch percepts can be implemented through non-simultaneous stimulation, with comparable pitch discrimination to that observed with simultaneous stimulation (Kwon and van den Honert, 2006).

A study compared the excitation patterns for simultaneous and sequential dual-electrode stimulation with the spread of neural excitation of a physical intermediate electrode using electrically evoked compound action potentials (Saoji, Litvak and Hughes, 2009). In this study, neural excitation patterns were determined for simultaneous nonadjacent dual-electrode stimulation, apical and basal-first sequential nonadjacent dual-electrode stimulation and the intermediate physical electrodes by using a masker-probe subtraction method. The neural excitation patterns were analysed in terms of their extent and centroid.

For simultaneous dual-electrode stimulation the extent and centroid of the neural excitation patterns were similar to those of the intermediate physical electrode (Saoji *et al*., 2009). However, the activation area of the sequential nonadjacent dual-electrode stimulation differed significantly from that of the intermediate physical electrode. There was a significant difference between the centroid of the neural excitation pattern of the apical-first sequential stimulation and that of the intermediate physical electrode (Saoji *et al*., 2009). In contrast, there was no significant difference between the centroid of the neural excitation of the basal-first sequential stimulation and that of the intermediate physical electrode (Saoji *et al*., 2009).

The contrast between the centre of gravity for apical-first and basal-first sequential stimulation is noteworthy, considering that the travelling wave travels from the cochlear base to the apex. The neural excitation patterns of the basal-first sequential stimulation were similar to those of the simultaneous stimulation. This might explain why either simultaneous or sequential stimulation can be used to achieve a current steering effect. It can also be used as an indication of how the sequential stimulation should be applied (basal-first) to obtain results similar to those of current steering experiments that made use of simultaneous stimulation.

2.6 SUMMARY

Increased spectral resolution might lead to better pitch and speech perception. Intermediate pitches can be elicited by stimulating either simultaneously or sequentially. Numerous studies have shown that a current steering effect can be achieved when simultaneous stimulation is used. Many different stimulation parameters and the effect of these parameters on current steering have been investigated. Some of these stimulation parameters include stimulation mode, electrode separation distance and stimulation amplitude levels. The number of spectral channels that can be created using current steering with simultaneous stimulation have also been carefully investigated.

Only a few studies have investigated current steering for cases where sequential stimulation is used. In all three available studies that investigated current steering with the use of sequential stimulation, the stimulation duration was 500 ms and the time between the pulses on the adjacent electrodes was chosen to be within the assumed refractory period of the neurons (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). The different sequential stimulation studies used different stimulation modes (bipolar or monopolar), different stimulation rates and different electrode separation distances. All three studies showed that current steering can be achieved when sequential stimulation is used. However, these studies were selective regarding the participants. For example, Swanson's study (2008) only included listeners who could effectively discriminate electrodes. It is not clear whether current steering can be achieved with sequential stimulation for all CI users.

The constraints and effects of different stimulation parameters on the pitch ranking ability of CI listeners (of stimuli created with the aim to achieve current steering effects by using sequential stimulation) require further investigation.

The following chapter details the primary experimental work of this study, which investigates current steering through sequential stimulation using different analysis methods. The effect of different stimulation parameters on current steering achieved using sequential stimulation is also investigated.

Previous current steering studies used pitch ranking experiments to determine if current steering can be achieved. The notion that intermediate pitches may be achieved with current steering is strongly based on place pitch theories. Literature suggests different features that may underlie place pitch. Comparing model predictions of different features with measured data may provide insight, and this is the theme of Chapter 4.

CHAPTER 3 PSYCHOACOUSTIC EXPERIMENTS

3.1 INTRODUCTION

Literature showed only a few studies that investigated the use of sequential stimulation to create a current steering effect. The objective of the psychoacoustic experiments that are reported in this chapter was to confirm that a current steering effect can be achieved using sequential stimulation. In addition, the experiments tested the effects of different stimulation parameters on the pitch ranking ability of CI listeners when stimuli were created with the aim to achieve current steering effects with sequential stimulation.

Section 3.2 discusses the method and the results of the current steering experiments. Section 3.3 discusses the method and the results of electrode pitch ranking experiments that were carried out to support the findings and the discussion of the current steering experiments. The key findings of this chapter are discussed and compared to other literature in Section 3.4.

3.2 CURRENT STEERING EXPERIMENTS

3.2.1 Method

3.2.1.1 Listeners

Nine experienced CI users, implanted with Nucleus[2] implants, participated in the experiments. Nine listeners were tested during the study, but the study included ten ears, since listener S3 completed the experiments using both her left and right ears. Relevant information with regard to each listener is listed in Table 3.1. The left ear of listener S3 was reimplanted because the original implant was faulty. Information on both the original and the present implant of the left ear of listener S3 is provided in Table 3.1. The relevance of

[2] http://www.cochlear.com

the information of the original implant was realised when the experimental results were analysed and this is discussed in Section 3.2.4.2.

Table 3.1. Background information on the nine listeners who participated in the experiments.

Lis-tener	Ear	Year of birth	Date of first MAP	Implant	Number of active electrodes	Stimu-lation rate per channel (Hz)	Stimu-lation pulse width (µs)	Stimu-lation mode
S3	Right	1949	2004	CI24R – Contour Advance	22	500	25	MP1+2
S3	Left (ori-ginal)	1949	1999	CI22M – Straight	18	240	25	BP+1
S3	Left (new)	1949	2007	CI24RE – Contour Advance	15	500	75	MP1+2
S25	Left	1980	2013	CI24RE – Contour Advance	22	900	25	MP1+2
S13	Left	1950	2005	CI24R – Contour Advance	20	900	25	MP1+2
S24	Right	1990	2006	CI24RE – Contour Advance	22	1200	25	MP1+2
S19	Right	1968	2006	CI24RE – Contour Advance	22	900	25	MP1+2
S28	Right	1953	2006	CI24RE – Contour Advance	22	1200	25	MP1+2
S6	Right	1956	2010	CI512 – Contour Advance	22	900	25 (10-13 =50)	MP1+2
S20	Left	1985	2004	CI24R – Contour Advance	21 (not 15)	900	25	MP1+2
S5	Left	1967	2013	CI24RE – Contour Advance	22	250	25	MP1+2

3.2.1.2 Stimuli

The experiments were carried out using the L34 research processor (provided by Cochlear Europe Ltd.), which was programmed by means of the Nucleus MATLAB toolbox (Swanson, 2008). After the stimuli had been created using the Nucleus MATLAB toolbox, it was confirmed to be correct before the external processors of the CIs of the listeners were replaced with the L34 research processor. The stimuli were tested by connecting the L34 to an implant-in-a-box (provided by Cochlear Europe Ltd.). This is a receiver-stimulator that is exactly the same as those that are implanted in CI users, with the output that would normally be connected to the implanted electrodes made available on measurements pins. This means that the implant-in-a-box provides access to the electrical signals applied to each electrode of a CI. These output signals of the implant-in-a-box were measured using a National Instruments PXI analog input module (PXIe-4300) that could sample 16 channels simultaneously. The PXIe-4300 had a sampling rate of 250 kS/s. The measured electrical pulse trains were visualised on a virtual oscilloscope on a computer.

Consideration of stimulation parameters

Pilot experiments were conducted to determine stimulation parameters that would be optimal for testing during the final experiments, in order to limit the number of experiments. Different stimulation parameters that may potentially have an influence on the effectiveness of current steering include stimulation amplitude, pulse rate, pulse width, the period between stimulation on the first electrode and the second electrode, stimulation mode (e.g. monopolar or bipolar mode), pulse phase conditions (e.g. burst mode or spread mode) and distance between stimulating electrodes. Figure 1.1 provides a visual explanation of the different stimulation parameters. The following few paragraphs explain why the parameters mentioned may potentially have an influence on the effectiveness of current steering.

Stimulus amplitude. Using higher stimulation amplitude for stimulation results in higher current output by the stimulating electrode. Stimulating neurons with higher current levels will result in a wider neural activation region compared to when neurons are stimulated with smaller currents (Goldwyn, Bierer and Bierer, 2010). Since the stimulation amplitude can influence the width of the neural activation region, it may influence the effectiveness of a current steering effect. Using very high stimulation amplitude when creating a current steering effect and activating too many neurons close to the stimulating electrodes might mask the current steering effect. However, using stimulation amplitudes that are too low might yield no neural activation.

Stimulus pulse width. Studies have shown that using wider pulse widths result in lower threshold values when the applied current level is kept constant (Shepherd and Javel, 1999). When the threshold is lower it can be assumed that there is a wider area of neural activation (Chatterjee and Shannon, 1998). This means that the stimulation pulse width can also influence the effectiveness of current steering. If the neural activation region is too small (and results in very soft sounds) owing to a low stimulation amplitude, increasing the pulse widths may improve the effectiveness of current steering by providing a wider activated neural population. In contrast, increasing the pulse widths may also mask current steering effects when it causes the neural activation region to become too large.

Stimulus pulse rate. Studies have shown that there is a relationship between the stimulation pulse rate and the perceived pitch (Pijl, 1995, Pijl and Schwarz, 1995a, Pijl and Schwarz, 1995b, Blamey *et al*., 1996, McDermott and McKay, 1997). The pitch perceived in response to the stimulation pulse rate is often referred to as rate pitch. Current steering effects are created by steering the current to different places along the auditory nerve, using multi-electrode stimulation. The pitch perceived due to current steering effects is proposed to be related to place pitch (Swanson, 2008). Because changing the pulse rate may alter the rate pitch, changes in the rate pitch might interfere with or influence the perception of place pitch and therefore influence the effectiveness of current steering in controlling pitch.

Interelectrode pulse delay. It has been stated that a current steering effect can only be achieved with sequential stimulation when the period between the stimulation on the first electrode and the stimulation on the second electrode is smaller than the refractory period of the neurons (McDermott and McKay, 1994). The refractory period of auditory neurons is about 1 ms (Avissar, Wittig, Saunders and Parsons, 2013). For this reason, the period between the stimulation on the first electrode and the stimulation on the second electrode was kept smaller than 1 ms for all the experiments carried out during this study.

Interelectrode pulse phase pattern. The pulse phase conditions (burst or spread mode) (Venter and Hanekom, 2014), used for stimulation during current steering ties in with the above-mentioned effect. Using burst mode means that the period between stimulation on the first electrode and stimulation on the second electrode is kept to a minimum. This period will only be as long as the pulse width and the inter-pulse delay used for stimulation on each electrode. Using spread mode would mean that the period between stimulation on the first electrode and stimulation on the second electrode is as large as the specific stimulation rate that is used during that experiment will allow. For example, if a pulse rate of 200 pps is used for stimulation, the period between stimulation on the first electrode and stimulation on the second electrode will be 2.5 ms. If it is true that current steering with sequential stimulation can only be implemented when the period between stimulation on the first electrode and stimulation on the second electrode is smaller than the refractory period of the neuron, it appears to follow that a current steering effect cannot be created using spread mode at a stimulation rate of 200 pps.

Stimulation mode. The stimulation mode, monopolar or bipolar stimulation might also influence the effectiveness of current steering. Using bipolar mode would mean that the current distribution would be much more concentrated in the cochlea, since both the active and the return electrode are within the cochlear duct. Monopolar stimulation would lead to very different current distribution patterns, since the return electrode is outside the cochlea. The different stimulation patterns (either monopolar or bipolar) would also look different for each CI user, because of structural differences between their cochleae, as well as different electrode placements within their cochleae.

Distance between electrodes. The distance between the stimulation electrodes during current steering may also influence how effective current steering will be. If the two stimulating electrodes are further away from each other, it may be easier to perceive a pitch between these electrodes. However, if the electrodes are too far away from each other, there may be no overlap between the different neural populations activated by the stimulating electrodes and consequently no current steering effect.

The parameters that were included in the pilot experiments were pulse phase conditions (burst mode or spread mode) (Venter and Hanekom, 2014), stimulation rate, stimulation amplitude, stimulation pulse width and distance between stimulating electrodes. Pitch ranking experiments were carried out to determine if these parameters influence the effectiveness of current steering effects. As mentioned before, the pitch perceived owing to current steering effects is proposed to be related to place pitch (Swanson, 2008) and that is why pitch ranking was used as a measure of current steering in the present study. The results of the pilot experiments showed that some of the parameters did not have a significant effect on the pitch ranking ability of the CI listeners. These parameters were excluded from the parameters that were tested in the final experiments. The pilot experiments and the results thereof are discussed in more detail in Appendix A.

The data of the pilot experiments suggested that changes in the stimulation pulse rate, electrode separation distance and stimulation pulse width made a noticeable difference (although not statistically tested) when the results were compared to the control experiment. No clear changes, compared to the control experiment, were observed in the data when the pulse phase conditions were changed or when the stimulation amplitude was altered.

Main experiments

Based on the results of the pilot experiments, the parameters that were tested in the main experiments included stimulation rate, stimulation pulse width and the distance between stimulating electrodes. Table 3.2 shows the 15 different experiments that were carried out. Experiment 1 served as the control experiment.

The parameters in Table 3.2 that were varied are illustrated in Figure 1.1. All the fixed stimulation parameters were chosen to be as close as possible to the default parameters used in the cochlear implant MAPs of the individual listeners. The inter-pulse delay (see Figure 1.1) was kept at a constant 8 µs, the same as the default inter-pulse delay used in the CIs of all nine listeners. Although not labelled this way in CI MAPs, burst mode is the pulse phase condition used by the speech processing algorithms of the CIs of the listeners. Since the pilot experiments suggested that the pulse phase condition does not have a significant effect on the pitch ranking ability of CI listeners of stimuli created to have a current steering effect, the default pulse phase condition, burst mode, was used in the experiments. Monopolar stimulation was used during the experiments, since this is the default stimulation mode of the CIs of the listeners tested in this study.

Table 3.2 Stimulation parameters used for each experiment.

Experiment number	Mode	Amplitude (Percentage of dynamic range)	Pulse width (µs)	Pulse rate (pps)	Period between 1st and 2nd burst (µs)	Electrode separation distance (Number of electrodes)
1	Burst	100	25	1776	70.4	1
2	Burst	100	25	1776	70.4	2
3	Burst	100	25	1776	70.4	3
4	Burst	100	25	888	70.4	1
5	Burst	100	25	888	70.4	2
6	Burst	100	25	888	70.4	3
7	Burst	100	25	200	70.4	1
8	Burst	100	25	200	70.4	2
9	Burst	100	25	200	70.4	3
10	Burst	100	79	1776	187.7	1
11	Burst	100	79	1776	187.7	2
12	Burst	100	79	1776	187.7	3
13	Burst	100	132	1776	281.5	1
14	Burst	100	132	1776	281.5	2
15	Burst	100	132	1776	281.5	3

Each parameter that was analysed by the experiments had three variations. The initial parameters chosen for Experiment 1 (see Table 3.2) were chosen because exactly the same parameters were chosen for another study (Swanson, 2008). Using the same parameters creates the opportunity to compare the results of the two studies. Literature shows that a fundamental limit to pulse rate discrimination in CIs may exist at 300 pps (Shannon, 1983, Tong *et al*., 1987, Townshend *et al*., 1987, McDermott and McKay, 1997, McKay *et al*., 2000, Zeng, 2002), although this is disputed by Venter and Hanekom (2014). Therefore, 200 pps, a stimulation rate below this proposed limit, was tested. The third pulse rate, 888 pps, was chosen since it is almost in the middle between 200 and 1776 pps. Using 888 pps rather than 788 pps, which is the exact centre of the higher and lower stimulation rate, ensured that the delay between the 1st and the 2nd burst could be kept at a constant 70.4 µs.

The 132 µs pulse width was chosen because it is the largest pulse width that can be applied at a stimulation rate of 1776 pps, since one period at this stimulation rate is equal to 0.563 ms. The 79 µs pulse width was chosen because it is exactly in the middle between 25 µs and 132 µs.

Each experiment was carried out with three different combinations of electrodes. A combination of electrodes 11 and 12, electrodes 11 and 13, and electrodes 11 and 14 was used. These electrodes are spaced 0.5 mm away from one another in the specific electrode arrays of the participants (namely: Contour Advance) (Cochlear, 2012). The electrode contacts have a width of 0.2 mm each (Cochlear, 2012). Thus, when electrodes 11 and 12 are used in the experiment, there is a space of 0.5 mm between them; when electrode 11 and 14 are used, there is a space of 1.9 mm between them. The closest electrode separation distance was selected because one of the objectives of the study was to confirm whether it was possible to create intermediate pitches between adjacent electrodes to improve the place pitch resolution of CI users, i.e., to confirm if a current steering effect can be achieved using sequential stimulation. The reason for including wider electrode separation as well was twofold. Firstly, not all CI electrode arrays have electrodes that are spaced as closely to one another as those used in the present study. For example, the Standard Med-El electrodes from their Classic series of electrodes are spaced 2 mm from each other (Cochlear, 2012). Secondly, if it is shown that current steering effects can still be obtained at larger electrode separation distances, current steering could be used to solve problems such as defective electrodes. Although seldom, electrode failure does sometimes occur after implantation of a cochlear implant (Chung, Kim, Parisier, Linstrom, Alexiades, Hoffman and Kohan, 2010).

If failure of only one or two electrodes occurred, current could be steered to activate the nerve fibres that used to be activated by the defective electrode.

3.2.1.3 Procedure

Fifteen experiments, with stimulation parameters as shown in Table 3.2, were conducted to evaluate the effect that changing the stimulation parameters would have on the pitch ranking ability of the listeners, when sequential stimulation was applied in a way that could possibly achieve a current steering effect. All 15 experiments were completed with each of the 10 different ears (nine CI users). Each of the experiments can be divided into three tasks: determining dynamic range, loudness balancing the stimuli and pitch ranking the stimuli.

Determining dynamic range

Firstly, the dynamic range for the specific set of parameters and the specific ear of the listener was determined. The pilot experiments showed that stimulating using two electrodes, even with sequential stimulation, results in slightly lower threshold and comfort levels. Since dual-electrode stimuli were used in these experiments (see Table 3.3), it was important to determine the dynamic range when both electrodes involved in the experiment were activated.

Apart from safety reasons, the purpose of determining the dynamic range in these experiments was to ensure that consistent perceptual levels were used in measurements for all the listeners. Stimulating with a fixed current (or fixed current units (CU[3]), in the terminology used in Nucleus cochlear implants) in all the listeners and for all the different stimulation parameters would not provide equal loudness for all the different stimuli. Selecting stimulation levels to be at a specific percentage of the dynamic range creates better consistency in loudness throughout the experiments and listeners.

To determine the dynamic range, the two electrodes involved in the specific experiment were stimulated for 0.5 s using the specific set of parameters. The listener was asked to move the

[3] Refer to Appendix B for a detailed definition of CU.

slider of a graphical user interface (GUI) on a personal computer (PC), which alters the amplitude of stimulation equally on both electrodes, until the stimulus was just audible. This amplitude was stored as the threshold. The listener then had to move the slider to a loudness that was the loudest comfortable sound. This amplitude was stored as the comfort level. The difference between the comfort level and the threshold level was the dynamic range. This process of determining the dynamic range was repeated three times. The difference between the mean of the three threshold levels and the mean of the three comfort levels was taken as the dynamic range.

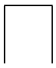
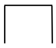
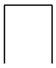
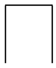
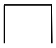
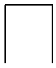
As expanded on later, each experiment consisted of four stimuli. Table 3.3 shows the four different stimuli. Note that 100% dynamic range was the dynamic range measured when electrode X and electrode Y were stimulating sequentially. When the amplitude was set to 100% of this dynamic range on a single stimulating electrode it was softer, but still comfortably audible compared to when the amplitude was set to 100% of the dynamic range of a dual-electrode stimulus. Once loudness roving (discussed later in this section) was added, using a stimulation amplitude of less than 100% of the dynamic range on a single electrode could result in sounds that were softer than comfortably audible sounds (i.e. sounds just louder than the threshold). Because none of the stimuli required stimulation of 100% of the dynamic range on both electrodes simultaneously, the stimuli were never louder than the comfort level of the listener.

Loudness balancing the stimuli

After the dynamic range of the two sequentially stimulating electrodes used during these experiments had been determined, custom stimuli, which were expected to create a current steering effect, were created with amplitudes as shown in Table 3.3.

The stimuli that were going to be used in the pitch ranking experiments (as shown in Table 3.3) had to be loudness-balanced to ensure equal loudness among each of the presented stimuli. Equal loudness of stimuli is important to ensure that loudness cannot be used as a cue during the experiment. Loudness balancing was carried out as demonstrated in an earlier study (van Wieringen, Carlyon, Laneau and Wouters, 2005). During loudness balancing, three stimuli were presented for 0.5 s each. The three stimuli were presented consecutively without any delay. The first stimulus and the third stimulus that were played were identical; these were the reference stimuli. The second stimulus was the test stimulus that had to be loudness-balanced to have the same loudness as the reference stimuli.

Table 3.3. Amplitude of the four stimuli used in each experiment. The last column shows a simple diagram to illustrate the amplitude of the stimuli of each electrode visually.

Name	**Stimulation current on electrode X (electrode 11)**	**Stimulation current on electrode Y (electrode 12/13/14)**	**Simple illustration of stimulation amplitude of stimuli as described by the preceding two columns**	
			Electrode X	**Electrode Y**
A	0	100% dynamic range		
B	100% dynamic range-15 CU	100% dynamic range		
C	100% dynamic range	100% dynamic range-15 CU		
D	100% dynamic range	0		

For the experiments of the present study, stimulus D (in Table 3.3) was used as the reference stimulus during the loudness balancing, i.e. all three stimuli, A, B and C, were loudness balanced against stimulus D. Stimulus A was the first stimulus to be loudness-balanced against D. The listener was asked to adjust a slider until all three stimuli (two reference stimuli and one balancing stimulus) sounded equal in loudness. When the listener moved the slider, only the amplitude of the balancing (middle) stimulus, in this case stimulus A, was varied. The amplitude of the reference stimuli, in this case stimulus D, was kept constant.

When stimulus B and stimulus C were loudness-balanced against the reference stimulus (stimulus D), the CU relationship between stimulating electrode X and electrode Y was kept the same as the CU relationship between stimulus D and stimulus A. While stimuli B and C were loudness-balanced, the CUs were adjusted on both electrodes X and Y simultaneously.

Table 3.4 is shown as an example of how the loudness balancing of the four stimuli (A, B, C and D in Table 3.3) used in the experiments was carried out.

Table 3.4 An example of loudness balanced stimuli.

Name	Stimulation current on electrode X (Current Units)	Stimulation current on electrode Y (Current Units)
D	190	0
A	0	189
B	187-15	186
C	190	189-15

As shown in Table 3.3, stimulus D consisted of the stimulation of electrode X at a current level of 100% of the dynamic range of the stimulating electrodes (i.e. the comfort level measured as described in the first section of Section 3.2.1.3) followed by the stimulation of electrode Y at a current level of 0 CU. For the example shown in Table 3.4, electrode X was stimulating with 190 CU while electrode Y was stimulating with 0 CU. Stimulus A consisted of the stimulation of electrode X at a current level of 0 CU, followed by the stimulation of electrode Y at a current level of 100% of the dynamic range of the stimulating electrodes. For the example in Table 3.4 this means that electrode X was stimulating with 0 CU while electrode Y was stimulating with 190 CU during the first step of the loudness balancing process. Note that after loudness balancing stimulus A to stimulus D, electrode Y in Table 3.4 was stimulating with 189 CU. This means that the reference stimulus (stimulus D) and the balancing stimulus (stimulus A) were equal in loudness when electrode Y used for stimulus A was stimulating at 1 CU softer than the comfort level of electrode X and Y when they were stimulated sequentially at equal loudness.

As shown in Table 3.3, stimulus B consisted of the stimulation of electrode X at a current level of 100% of the dynamic range of the stimulating electrodes minus 15 CU, followed by the stimulation of electrode Y at a current level of 100% of the dynamic range of the stimulating electrodes. For the example in Table 3.4 this means that electrode X was stimulating with 175 CU and electrode Y was stimulating with 190 CU during the first step of the loudness balancing process of these two stimuli. However, the 1 CU difference between electrode X of stimulus D and electrode Y of stimulus A had to be kept constant.

This means that during the first step of the loudness balancing process of these two stimuli (D and B), electrode X was stimulating with 175 CU but electrode Y was actually stimulating with 189 CU. As explained earlier in this section, the CUs were adjusted on both electrodes X and Y simultaneously when stimulus B was loudness-balanced against stimulus D. Table 3.4 shows that after stimulus B was loudness-balanced against stimulus D, electrode X was stimulating with 187-15 = 172 CU and electrode Y was stimulating with 186 CU. This means that the reference stimulus (stimulus D) and the balancing stimulus (stimulus B) were equal in loudness when electrode Y used for stimulus B was stimulating at 4 CU softer than the threshold level of electrode X and Y when they were stimulated sequentially at equal loudness. The loudness balancing of stimulus C to stimulus D works the same as the loudness balancing of stimulus B to stimulus D.

As a further precaution to prevent the listeners from using loudness as a cue, loudness roving was added to each stimulus played during the third and final stage of the experiment. Similar to other studies, a loudness roving range of +/- 10 % of the dynamic range of the listener was chosen (Laneau and Wouters, 2004, Snel-Bongers, Briaire, Vanpoucke and Frijns, 2012). This means that the stimulus could be up to 10% of the dynamic range louder or 10% of the dynamic range softer than the loudness-balanced stimulus. The current applied was increased by equal amounts for both stimulating electrodes. This ensured that the ratio of current applied between the two stimulating electrodes remained the same.

Pitch ranking of stimuli

For the third and final stage of each of the 15 experiments, the listeners were asked to pitch rank each of the four stimuli against one another. A 2AFC method was used to perform the pitch ranking. A stimulus randomly selected from A, B, C or D was played for 0.5 s, followed by 0.5 s of silence, followed by another random stimulus (A, B, C or D), which was also played for 0.5 s. The listener then had to indicate which one of the two sounds was higher in pitch. The listeners could listen as many times as they wished to the two stimuli before making a decision. No feedback was given to the listener during the experiments. Each combination of two stimuli was presented 10 times. This means that stimuli A and D were presented together 20 times; A followed by D 10 times and D followed by A 10 times.

3.2.2 Multidimensional scaling

After all the different combinations of stimuli had been presented to the listener, the results were tabulated in a stimulus-response matrix format. Figure 3.1 is an example of the stimulus-response matrix for experiment 1 of listener S3. The stimulus-response matrix shows how many times the stimuli shown by each column were rated higher than the stimuli shown by each row. For example, stimulus A was judged to be higher than stimulus B eight out of 20 times.

	A	B	C	D
A	10	12	18	20
B	8	10	17	20
C	2	3	10	20
D	0	0	0	10

Figure 3.1 Stimulus-response matrix of the data of experiment 1 of listener S3. This matrix is an example of the input used to determine the dissimilarity matrix for the MDS.

The pitch rank order of the different stimuli was determined using multidimensional scaling (MDS) methods. MDS analysis maps each stimulus in the matrix into a multidimensional (or *N*-dimensional) space (Collins and Throckmorton, 2000, van Wieringen and Wouters, 1999). The MDS algorithm attempts to find an optimal solution to the problem of placing each stimulus as a point in some multidimensional space so that distances or dissimilarities captured by the stimulus-response matrix are reflected as distances within this space. To achieve this, the stimulus-response matrix first had to be converted into a dissimilarity matrix. The matrix was converted to a dissimilarity matrix using

$$d_{ij} = \sum_{k=1}^{4} \left| c_{ik} - c_{jk} \right|, \tag{3.1}$$

where d_{ij} represents the entry in column j of row i of the dissimilarity matrix, c_{ij} represents the entry in column j of row i of the stimulus-response matrix and k is the index used to count through the rows or the columns (Swanepoel *et al*., 2012). An example of the dissimilarity matrix for the data shown in Figure 3.1 is shown in Figure 3.2. In the dissimilarity matrix, larger numbers indicate greater dissimilarity between the stimuli, while smaller numbers are an indication of greater similarity between stimuli. For example, the dissimilarity matrix in Figure 3.2 shows that, as expected, there is large dissimilarity between stimulus A and stimulus D, and that stimulus A and stimulus B are more similar. This also explains the zeros on the diagonal.

	A	B	C	D
A	0	5	25	50
B	5	0	20	45
C	25	20	0	25
D	50	45	25	0

Figure 3.2 Dissimilarity matrix of the data of experiment 1 of listener S3. This dissimilarity matrix is an example of the matrix used as input to do MDS.

Once the dissimilarity matrix had been found, MDS was carried out using built-in MATLAB functions. The number of dimensions that need to be used for an MDS analysis is determined by considering a factor called the stress of the analysis. The stress is calculated by

$$Stress = \sqrt{\frac{\sum_{i<j}\left(f\left(x_{ij}\right) - d_{ij}\right)^2}{\sum_{i<j} d_{ij}^2}}, \tag{3.2}$$

where d_{ij} refers to the euclidean distance, across all dimensions, between points i and j on the MDS map, and $f(x_{ij})$ is a function of the input data (Kruskal, 1964). Using nonmetric MDS, x_{ij} denotes the upper or lower triangle of the dissimilarity matrix and $f(x_{ij})$ is a monotonic transformation of the input data that minimizes the stress function (Kruskal, 1964). Monotonic regression is used to compute the monotonic transformation.

There are different opinions on how the stress should be interpreted. Originally Table 3.5, determined empirically, was proposed for interpretation of MDS stress results (Kruskal, 1964).

Table 3.5 Table used to interpret the goodness of fit of data using a certain number of dimensions based on the stress value of the data.

Stress	Goodness of fit
>.20	Poor
.10	Fair
.05	Good
.025	Excellent
.00	Perfect

The value of stress is highly dependent on the number of entries in the dissimilarity matrix. Therefore, more recent research studies tend to use other methods, such as scree plots, to determine the number of dimensions that should be used (Wickelmaier, 2003). Scree plots show the amount of stress plotted against the number of dimensions. The best fitting MDS model will have the lowest number of dimensions with acceptable stress. Considering Figure 3.3, it is seen that the stress decreases relatively quickly from one dimension to three dimensions, after which the rate at which the stress decreases seems to stabilise. The number of dimensions in the MDS model with best fit is found at the point in the scree plot where the slope changes from steep to shallow. Some literature refers to this point as the “elbow” (Wickelmaier, 2003).

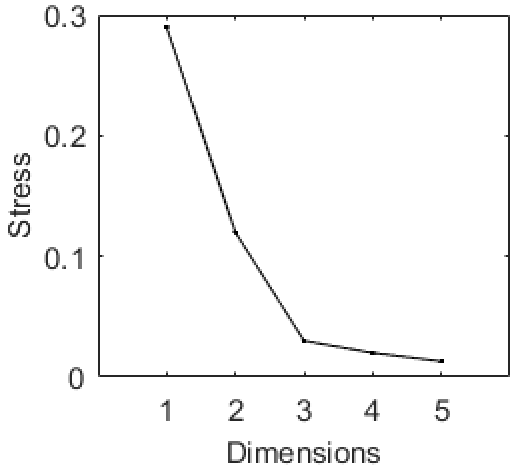


Figure 3.3 Example of a scree plot, used to determine the number of dimensions that should be used for MDS.

Figure 3.4 shows the scree plots for the data of the different experiments completed by listener S3 with her right ear.

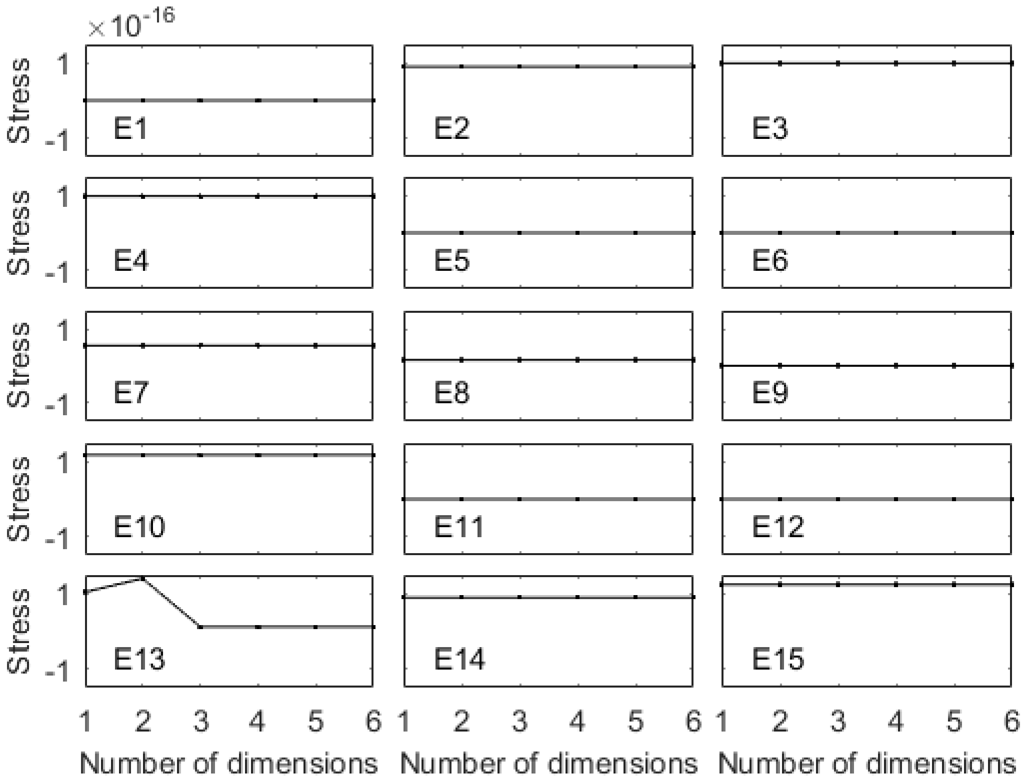


Figure 3.4 Scree plots of the data of all the experiments of listener S3R.

Figure 3.4 shows that for most of the experiments there is no change in stress as the number of dimensions increases. The goodness of fit when using only one dimension is “Perfect” (with reference to Table 3.5). The one experiment that does show a change in the slope of the plot, change in the range between 0 and 1×10^{-16}. Even though the graph has an elbow, the stress is extremely low and the data can still be represented in one dimension. This is interpreted as meaning that the listener used a single perceptual dimension when judging pitch direction, and that the four stimuli could be ranked in this dimension. This dimension is interpreted to be a pitch dimension, given that stimuli were carefully loudness-balanced.

Having determined that a one-dimensional MDS analysis would be appropriate, the MDS analysis was carried out. The MDS results for all the experiments for the different listeners are shown in Figure 3.5. The results of the MDS show both the order in which the stimuli were ranked and the perceptual distance between the different stimuli. Note that the MDS uses an arbitrary scale. The MDS does not indicate which of the four stimuli is highest or lowest in pitch. It just gives the order in which the stimuli follow on one another, i.e. the axis could be from high to low or from low to high. Consequently, this means that the order A, B, C, D could be the same as the order D, C, B, A, arranged from high to low and low to high respectively. To determine if the MDS ordered the data from high to low or from low to high, the d'_{DA} was calculated. d'_{DA} was used rather than d'_{DC}, d'_{DB}, d'_{CB}, d'_{CA} or d'_{BA} because the listener was least likely to confuse the pitch of stimuli A and D.

Apart from MDS, d' values provide another way of calculating perceptual distance. d' values are calculated by

$$d' = Z(hit\ rate) - Z(false\ alarm\ rate), \tag{3.3}$$

where $Z(p)$, $p \in [0,1]$, is the z-score, that correspond to the right-tail probabilities (p) on the normal distribution. If one is calculating d'_{DA}, the $hit\ rate$ represents the number of times the listener perceived stimulus D higher than stimulus A, when stimulus D was presented first and stimulus A was presented second during the pitch ranking experiment. The $false\ alarm\ rate$ represents the number of times the listener perceived stimulus A higher than stimulus D when stimulus A was presented first and stimulus D was presented second during the pitch ranking experiment. If $d'_{DA} > 0$, stimulus D was ranked higher in pitch than stimulus A and if $d'_{DA} < 0$, stimulus A was ranked higher in pitch than stimulus D.

The number of decimal places to which p is rounded determines the maximum finite value of d' (Macmillan and Creelman, 2005). The present study made use of a normal distribution table, which included p values with up to six decimals (Montgomery and Runger, 2011). The largest and smallest Z values were therefore equal to 3.99 and -3.99 respectively (Montgomery and Runger, 2011). Note that perfect accuracy implies an infinite d' (Macmillan and Creelman, 2005). This means that if the $hit\ rate$ or the $false\ alarm\ rate$ is equal to 0 or 1 the Z transform reaches infinity. To account for this, an approach was followed where if $p = 0$, p was assigned the smallest value in the normal distribution table $p = 0.000033$; if $p = 1$, p was assigned the largest value in the normal distribution table, $p = 0.999967$ (Iverson and Kuhl, 1996).

Assuming that a current steering effect could be achieved using sequential stimulation, it was expected that the listeners would rank the stimuli in the order A, B, C, D, where A is lowest in pitch and D is highest in pitch. Considering the MDS results, Figure 3.5 shows that when current-steered stimuli were applied in the right ear of listener S3, the listener could rank the stimuli in the expected order irrespective of the particular stimulation parameters (with reference to Table 3.2) in the specific experiment. Using d'_{DA} it was determined that the pitch order of all the experiments of listener S3R was ranked from the lowest pitch to the highest pitch.

Listener S3 did not perform as well with the left ear as with the right ear. Two characteristics of the data of listener S3L in Figure 3.5 are of interest. Firstly, the perceptual distance between the different stimuli was much smaller than in her right ear. The MDS results of listener S3L were much more clustered than the spread-out perceptual distances seen from her right ear. More clustered data as opposed to data with larger perceptual distances between stimuli means that the listener had greater difficulty distinguishing between the different stimuli. Secondly, very few of the pitch ranking orders of the different experiments corresponded to the expected order.

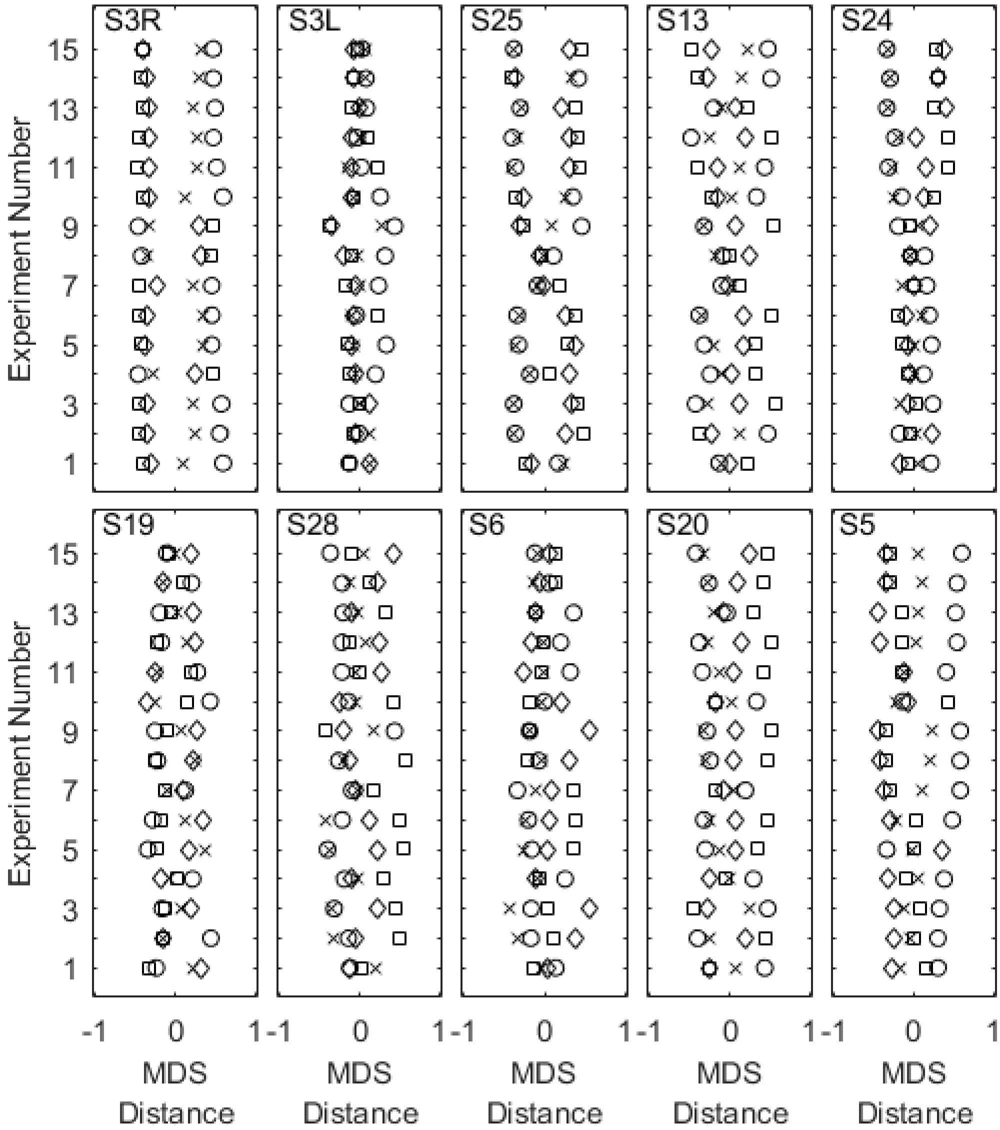


Figure 3.5. Scaled MDS result for all the experiments of all the listeners. The y-axis shows the experiment number, while the x-axis shows the position of each stimulus along the one-dimensional axis as determined by MDS, which represents perceptual distance. Stimuli A, B, C and D are represented by a square, diamond, cross and circle respectively.

The results of listener S25 show that the listener could clearly distinguish the pitch of stimuli A and B from the pitch of stimuli C and D. The listener often confused stimulus A with stimulus B and vice versa as well as stimulus C with stimulus D and vice versa. The perceptual distance from stimuli A and B to stimuli C and D was much larger than the perceptual distance between stimulus A and stimulus B or the perceptual distance between stimulus C and stimulus D. Stimulus D was ranked higher in pitch than stimulus A in each of the 15 experiments completed by listener S25.

Figure 3.5 shows that listener S13 was almost always able to rank the stimuli in the expected order, the exceptions being experiments 7, 8 and 9. The common stimulation parameter that distinguished these three experiments from the control experiment were the pulse rate, being 200 pps for experiment 7, 8 and 9. This was the lowest pulse rate the different experiments tested. Stimulus D was always ranked higher in pitch than stimulus A irrespective of the experiment that was carried out.

Even though listener S24 was able to rank the stimuli of some of the experiments in the expected order, Figure 3.5 shows that this listener confused many of the stimuli, and stimuli were often ranked in an order other than expected. When compared with the data of listener S3R, many of the MDS results of the different experiments of the data of listener S24 seem to be more clustered. Even though most of the pitch ranking orders of the different experiments were different from the expected order, stimulus D was always ranked higher in pitch than stimulus A.

Figure 3.5 shows that listener S19 was unable to rank any of the stimuli in the expected order. Many of the results were clustered. There is some trend in the data that shows that the listener might have been able to distinguish the pitch of stimuli A and D from the pitch of stimuli B and C. There was some confusion between the pitch of stimulus A and stimulus D as well as between the pitch of stimulus B and stimulus C. The sensitivity index d'_{DA} showed that the listener ranked stimulus A higher than stimulus D for experiments 2 to 6 and experiments 9 to 11.

Listener S28 was able to rank some of the stimuli of the different experiments in the expected order. Figure 3.5 shows that the stimuli of the different experiments of this listener were generally ranked in the expected order, but sometimes with one of the stimuli out of place. It was confirmed by using d'_{DA} that the listener ranked stimulus A higher than stimulus D for experiments 1 to 6 as well as experiments 8 and 9. This means that some of the stimuli that mostly seem to be ordered in the expected order (from low to high) could actually be ordered in exactly the opposite order (from high to low).

The data of may experiments completed by listener S6 were clustered. It seems as if listener S6 found it rather difficult to order the stimuli in any order. Considering d'_{DA} values, this listener also ranked stimulus A higher than stimulus D in experiments 1, 4, 7, 8, and 13.

Similar to the results of listener S25, listener S20 was able to distinguish the pitch of stimuli A and B clearly from the pitch of stimuli C and D. The data of listener S20 are also shown in Figure 3.5. The listener sometimes confused stimulus A with stimulus B and vice versa as well as stimulus C with stimulus D and vice versa. The perceptual distance from stimuli A and B to stimuli C and D was much larger than the perceptual distance between stimulus A and stimulus B or the perceptual distance between stimulus C and stimulus D. Listener S20 ranked stimulus D higher in pitch than stimulus A in all 15 experiments. This was confirmed by considering the d'_{DA} values.

Listener S5 did not order all the stimuli in the expected order for any of the experiments. Figure 3.5 does show that in many experiments this listener was able to rank the stimuli in almost the expected order, only confusing stimulus A and stimulus B. Considering the d'_{DA} values it was observed that this listener also always ranked stimulus D higher in pitch than stimulus A.

The MDS results shown in Figure 3.5 were used to draw cumulative MDS graphs, similar to cumulative d' graphs often seen in literature (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). The cumulative MDS graphs are shown in Figure 3.6

and Figure 3.7. These graphs emphasise the observations in Figure 3.5. Since the cumulative MDS was derived from the MDS that was calculated in a one-dimensional space, $S_{AC}=S_{AB}+S_{BC}$ and $S_{AD} = S_{AB}+S_{BC}+S_{CD}$, where S_{XY} is the perceptual distance (in arbitrary MDS units) between the position of stimulus X and the position of stimulus Y along the MDS axis.

The always positive gradient of the graphs of each experiment in the first panel of Figure 3.6 shows that listener S3 was able to rank all the stimuli of all the experiments for her right ear in the expected order. A small gradient (for example between stimulus A and stimulus B of experiment 15 of the right ear of listener S3) shows that the perceptual distance between these two stimuli is rather small, while a larger gradient like that between stimulus B and stimulus C of the same experiment shows that the perceptual distance between those two stimuli is bigger.

A negative gradient such as the one between stimulus B and stimulus C of experiment 15 in the data of subject S3L in Figure 3.6 shows that stimulus C was ranked lower in pitch than stimulus B. The expected rank order would have been that stimulus C should have been ranked higher in pitch than stimulus B. Using her left ear, listener S3 only seemed able to rank the stimuli of experiments 7, 8 and 9 in the expected order easily. These three experiments were carried out at the lowest pulse rate, 200 pps. The stimuli of the other experiments were either ranked in an unexpected order or the perceptual distance between the different stimuli was very small.

The cumulative MDS results of listener S25 in Figure 3.6 confirm the observations made from the data of this listener in Figure 3.5. In addition, the results in Figure 3.6 show that the perceptual distance between stimuli of experiments 7, 8 and 9 are much smaller than the perceptual distance between stimuli in any of the other experiments. It is observed that listener S25 had trouble ranking the stimuli of experiments 7, 8 and 9 compared to ranking the stimuli of the other experiments. This is contrary to the observations of the left ear of listener S3.

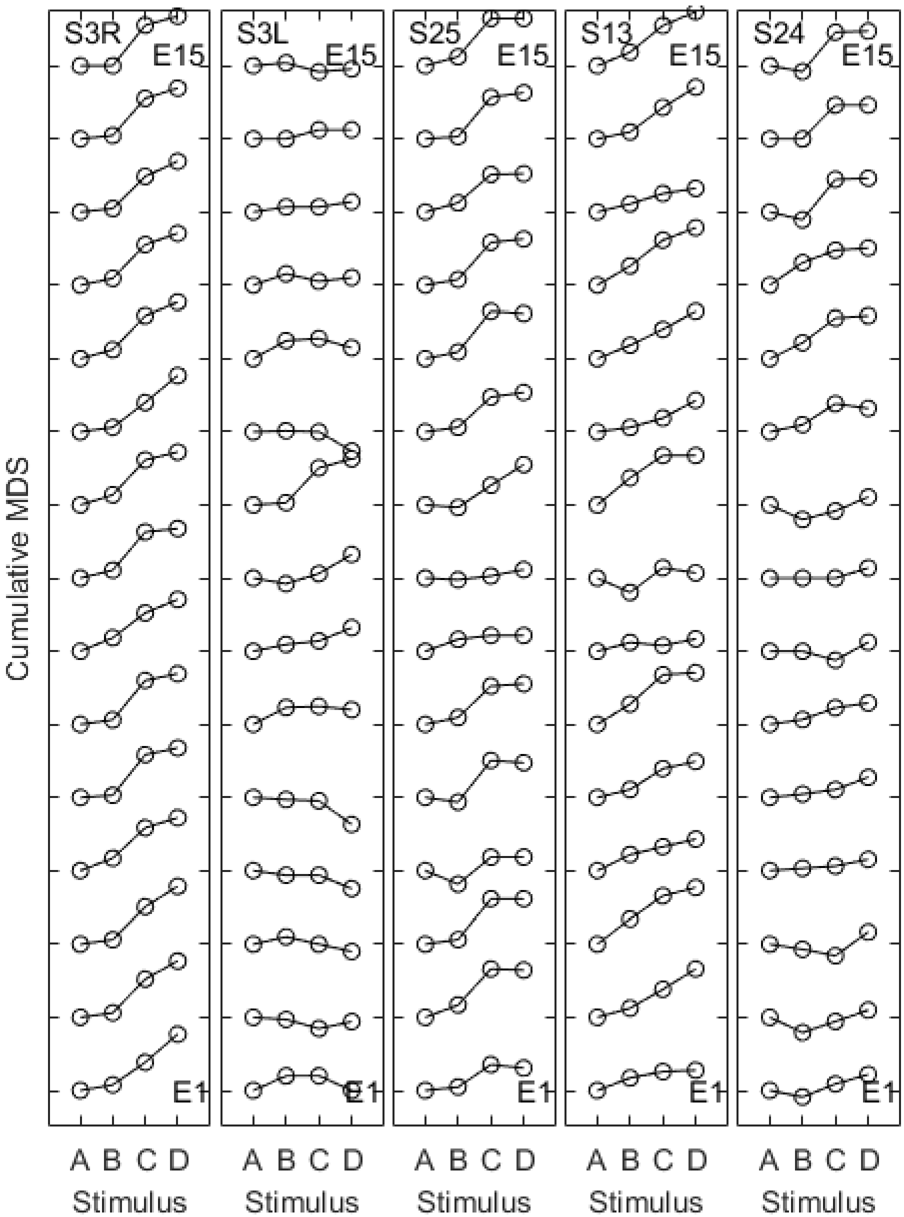


Figure 3.6. Cumulative MDS graphs for the first five listeners in Table 3.1. Each panel consists of 15 cumulative MDS graphs, one for each experiment. The cumulative MDS graph closest to the x-axis is the graph of experiment 1 and the cumulative MDS graph furthest away from the x-axis is the graph of experiment 15. Each cumulative MDS graph was plotted from -65 to 65. There are 15 ticks on the y-axis. Each of these ticks represents the 0 mark of the cumulative MDS graph of the corresponding experiment. This means that the first tick on the y-axis represents the 0 mark of the cumulative MDS graph of experiment 1, but it also represents the -65 mark of the cumulative MDS graph of experiment 2. The second tick on the y-axis represent the 65 mark of experiment 1, the 0 mark of experiment 2 and the -65 mark of experiment 3 and so on.

Similar to the results of listener S25, Figure 3.6 shows that listener S13 had difficulty ranking the stimuli of experiments 7 and 8. The perceptual distance between the stimuli were small and the listener was unable to rank the stimuli in the expected order. Just as the data of this listener in Figure 3.5 suggested, this listener was able to rank the stimuli of all the other experiments into the expected order easily.

Figure 3.6 and Figure 3.7 show that listener S24 and listener S19 had great difficulty in ranking the stimuli. The order of the pitch ranking results differed from the expected order. The results of these listeners showed that the perceptual distance between stimuli was much smaller compared to that of some of the other listeners. The results of listener S24 did seem to improve for the last six experiments where the pulse widths were wider than those of the control experiment.

For most experiments listener S28 was unable to rank the stimuli in the expected order. Figure 3.7 shows that for this listener the perceptual distance between the different stimuli was rather large. However, for most of the experiments this listener arranged the stimuli in an order opposite to the expected order. The pitch rank order only looked more similar to the expected order after the pulse width had been increased compared to the control experiment (experiments 10 - 15).

Figure 3.7 confirms the initial observations made from the data of S6 in Figure 3.5. Irrespective of the experiment, the perceptual distance between the stimuli was very small compared to those of other listeners. This listener did not rank the stimuli in the expected order. In fact, it seems as if listener S6 ranked the stimuli in random order.

Listener S20, of whom cumulative MDS results are also plotted in Figure 3.7, performed according to expectation. For most experiments, this listener ranked the stimuli in the expected pitch rank order. The perceptual distance between the different stimuli was large.

Figure 3.7 shows that listener S5 found it difficult to rank the stimuli of most experiments in the expected order. Similar to listener S3, this listener did perform well in experiments 7, 8 and 9, which were carried out at the lowest pulse rate. The listener also seemed to perform a little better in the last six experiments where a wider pulse width was implemented compared to the first six experiments.

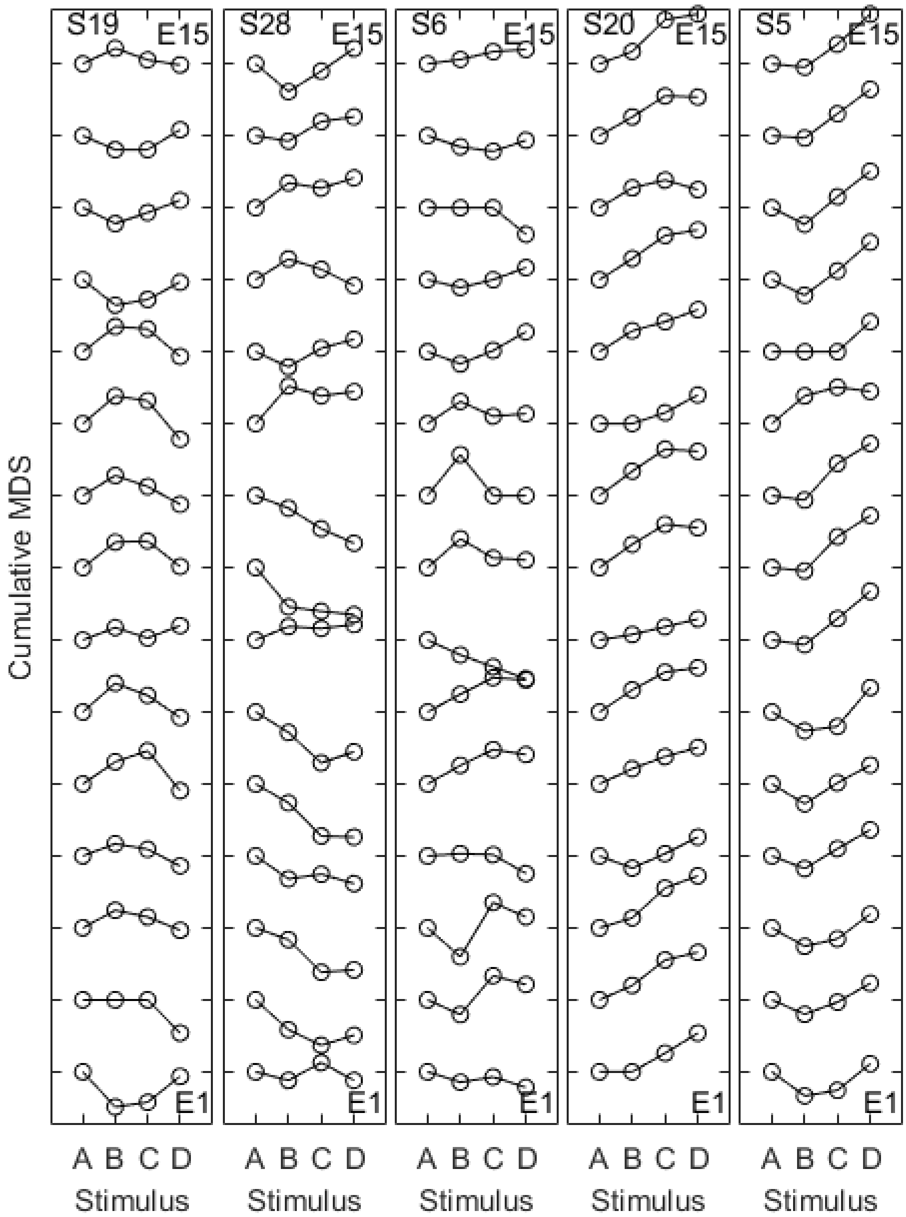


Figure 3.7. Cumulative MDS graphs for the last five listeners in Table 3.1. These graphs should be interpreted in the same way as those in Figure 3.6.

In conclusion of the MDS results, the following can be said.

- No single consistent trend appeared across the experiments for all the listeners, but the results of some listeners were similar for certain stimulation parameters. These similarities among listeners are highlighted in the points that follow.
- Listener S3R was the only listener who was able to rank the stimuli of all 15 experiments in the expected order. On average, over all the experiments, the largest perceptual distance between stimulus A and stimulus D was found when the results of this listener were considered.
- Most listeners were able to distinguish between stimulus A and stimulus D and, as expected, ranked stimulus D higher than stimulus A. However, two listeners, S19 and S28, often ranked stimulus A higher than stimulus D.
- For a few listeners, for example S5 and S28, larger perceptual distances were observed between stimuli for the experiments where wider stimulation pulse widths were used.
- Another observation was that there seemed to be a noticeable change in the perceptual distance between stimuli for the experiments where a pulse rate of 200 pps was used. Some listeners, for example S3L and S5, seemed to perform better at these experiments, while others, for example S13 and S25, performed well in all the experiments except the experiments carried out at 200 pps.

The MDS results show the perceptual distance between stimuli, as well as the pitch rank order for the different stimuli for each experiment of the different listeners. They only give a rough indication of whether a current steering effect can be achieved using sequential simulation for the different listeners, and whether certain stimulation parameters lead to more accurate pitch ranking results than others. Statistical analyses were carried out to determine if current steering can be achieved using sequential stimulation, i.e. if the current steering effect with the present set of stimuli was statistically significant. Statistics were also calculated to determine if the different stimulation parameters that were used had a significant effect on the ability of the listeners to perform pitch ranking of stimuli created using a current steering effect accurately. The process and results of the statistical analysis are presented in Section 3.2.4.

3.2.3 Cumulative d'

The previous section showed cumulative MDS-derived perceptual distances. Literature has shown that many experimenters prefer to use cumulative d' values to express the perceptual distance between stimuli (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). Equation (3.3) showed how d' can be calculated. When cumulative d' values are used to express the perceptual distance between perceived pitches, they are used under the assumption that the perceptual dimension of pitch is unidimensional (Kwon and van den Honert, 2006). Cumulative d' values are calculated by

$$d'_{X,Y} = d'_{X,A} + d'_{A,Y}, \tag{3.4}$$

where for example in the present study X and Y are the positions of the pitches of the two stimulating electrodes and A is a pitch somewhere between X and Y.

It has, however, been shown that perceptual data of non-simultaneous dual-electrode stimuli in cochlear implantees can be described by a two-dimensional space (McKay, McDermott and Clark, 1996). That study was conducted using bipolar stimulation. The number of dimensions necessary to describe perceptual data when sequential dual-electrode, monopolar stimulation is used cannot be assumed to be the same as the results for bipolar stimulation. The study of McKay *et al*. (1996) also suggested that often, but not always, perceptual data of dual-electrode stimuli could be represented by a single dimension in the range between two corresponding single-electrode stimuli, on condition that the inter-electrode delay is less than the refractory period of the neurons. No available literature appears to suggest that pitch perception should be unidimensional when monopolar stimulation is used. MDS, and more specifically the stress factor of MDS, can be used to determine the number of dimensions that would be most suitable to represent pitch ranking data obtained through monopolar stimulation.

As discussed in Section 3.2.2 and shown by Figure 3.4, pitch ranking data obtained through monopolar stimulation can indeed be represented in a unidimensional space. These findings correspond to the results obtained by McKay *et al*. (1996), who used bipolar stimulation.

In addition to the cumulative MDS values shown in Figure 3.6 and Figure 3.7, cumulative d' values were calculated for the different stimuli of the experiments of the present study. The results are shown in Figure 3.8 and Figure 3.9. These two figures show that although the scale of perceptual distance is different between cumulative MDS and cumulative d', the two methods produce very similar results when the shape of the curves of each corresponding experiment of each listener is considered, i.e. the corresponding experiments of most listeners were ranked in the same order irrespective of whether MDS or d' were used and the relative change in distance between the different stimuli of a specific experiment of a specific listener was similar when the cumulative d' graphs were compared to the cumulative MDS graphs. Although most corresponding graphs showed similarities, some also showed discrepancies with stimuli that were ranked in different orders.

Listeners S3R, S20 and S5 are examples of where the cumulative d' graphs of most of the experiments of each of the users were very similar to the cumulative MDS graphs. The order in which the stimuli were ranked, as well as the relative change in distance between the different stimuli, was very similar. Figure 3.5 was considered along with the cumulative MDS graphs and it was seen that all the stimuli of most of the experiments of these listeners were perceptually relatively far from one another compared to the results of, for example, listener S3L.

Experiments 7, 12, 13 and 14 of listener S19, on the contrary, are examples of discrepancies between the cumulative d' results and the cumulative MDS results. The perceived pitches of stimuli in these experiments were ranked in a different order when the cumulative d' results were compared to the cumulative MDS results. It was interesting to see that Figure 3.5 along with the cumulative MDS graphs showed that the stimuli of these experiments were clustered and not nearly as spread out across the MDS as those of most of the experiments of listeners S3R, S20 and S5.

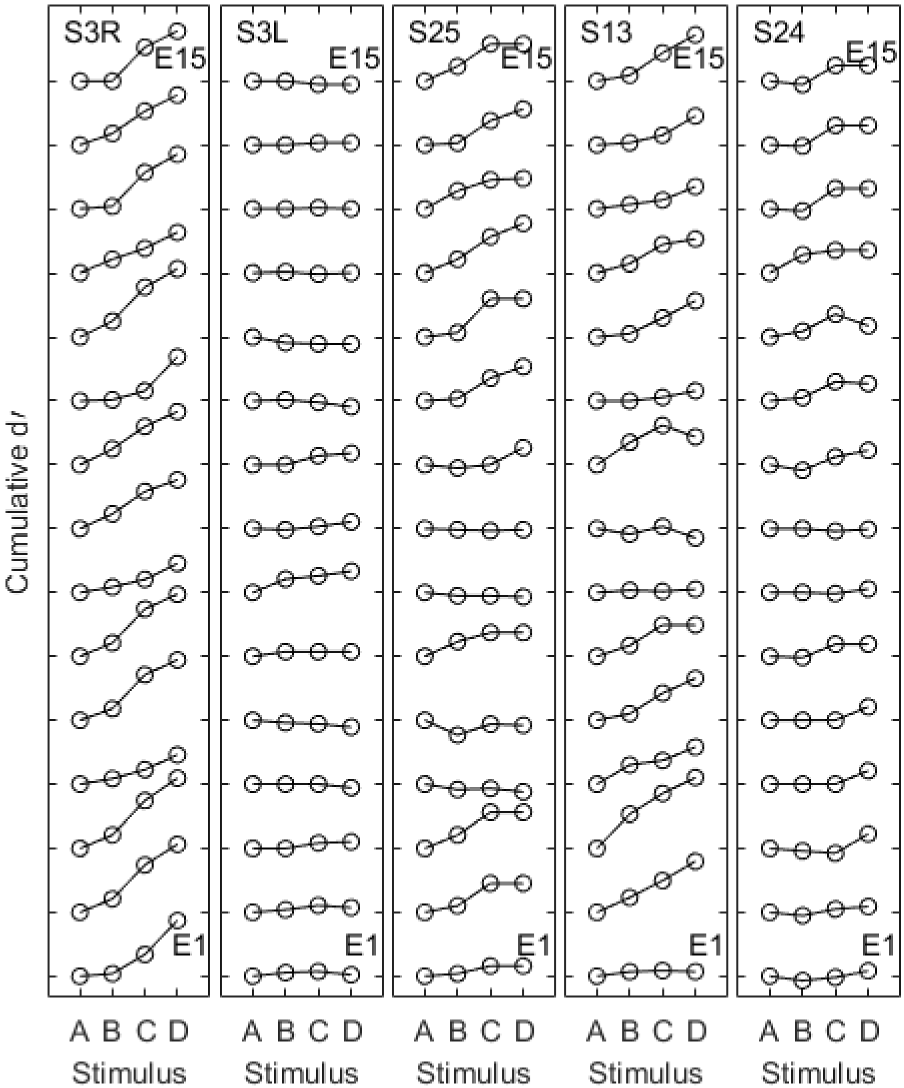


Figure 3.8 Cumulative d' graphs for the first five listeners in Table 3.1. Each panel consists of 15 cumulative d' graphs, one for each experiment. The cumulative d' graph closest to the x-axis is the graph of experiment 1 and the cumulative d' graph furthest away from the x-axis is the graph of experiment 15. Each cumulative d' graph was plotted from -15 to 15. The 15 ticks on the y-axis each represents the 0 mark of the cumulative d' graph of the corresponding experiment. The first tick on the y-axis represents the 0 mark of the cumulative d' graph of experiment 1 and the -15 mark of the cumulative d' graph of experiment 2. The second tick on the y-axis represent the 15 mark of experiment 1, the 0 mark of experiment 2 and the -15 mark of experiment 3 and so on.

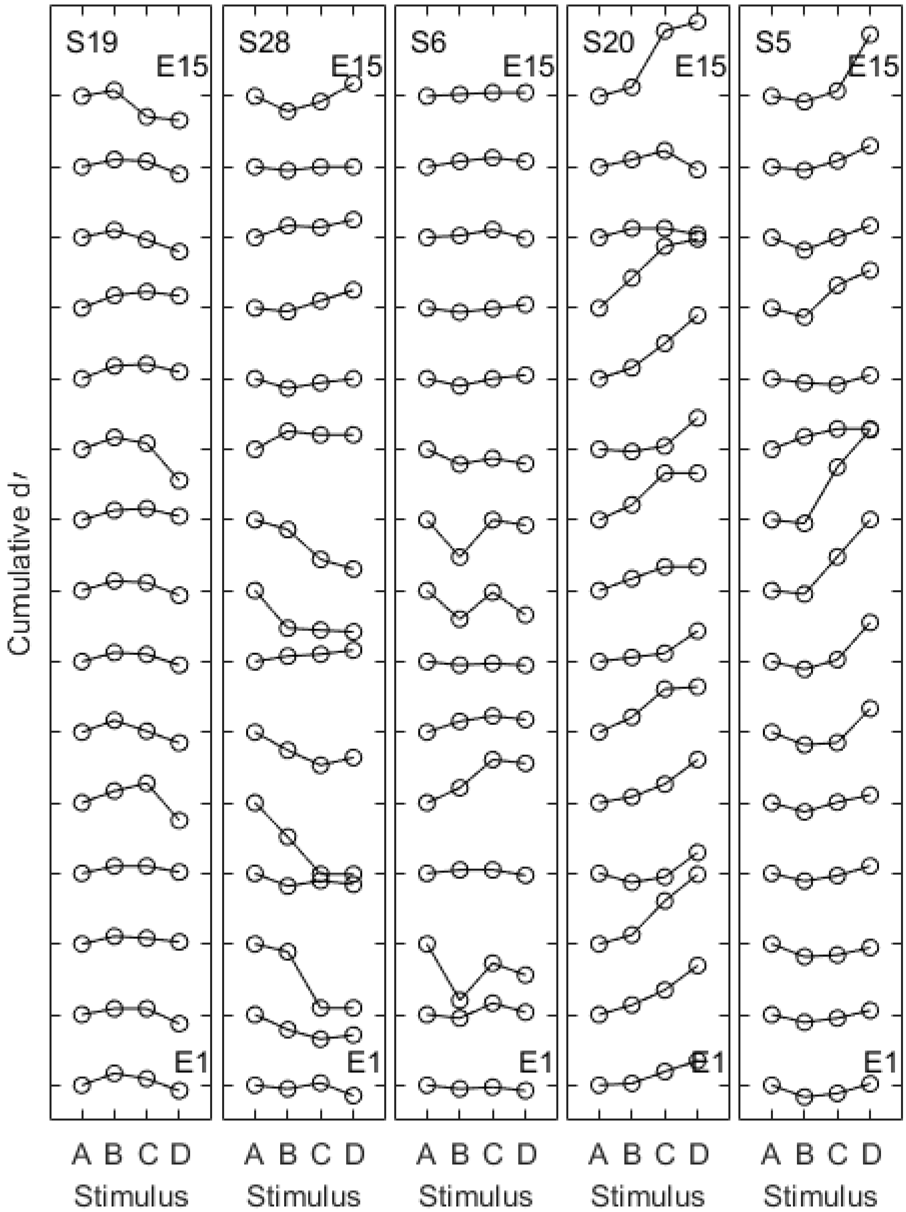


Figure 3.9 Cumulative d' graphs for the last five listeners in Table 3.1. These graphs should be interpreted in the same way as those in Figure 3.8.

It was interesting to note that the cumulative MDS and cumulative d' graphs were more similar when the perceptual distance between stimuli were larger, while the graphs were less similar when the perceptual distance between stimuli were smaller. The aforementioned discrepancies probably occur because d' values only consider the perceptual distance between two stimuli at a time. MDS, on the contrary, considers all four stimuli simultaneously and finds the pitch rank order and perceptual distance between the stimuli that best represent the perceptual distance between all four stimuli in a single dimension. Considering all four stimuli simultaneously is assumed to lead to a more accurate result, especially when the perceptual distance between the stimuli is small. Another factor to consider, which might have led to the discrepancies, is the fact that the pitch rank order has to be assumed when cumulative d' values are used to express perceptual distance between stimuli. Assuming an incorrect rank order could lead to inaccurate results, especially when the stimuli are very similar to one another and the perceptual distance between the stimuli is very small.

The stimulation parameters of the control experiment, experiment 1, of the present study and the stimulation parameters used by Swanson (2008) were identical. Swanson (2008) showed that all the listeners who participated in that pitch ranking study could pitch-rank the stimuli in the expected order when these stimulation parameters were used. For this reason, these stimulation parameters seemed like an appropriate choice. The stimulation parameters of experiment 1 were also chosen for easy comparison between the results of the present study and that of Swanson (2008). The cumulative d' results for experiment 1 of all the listeners that were also presented in Figure 3.8 and Figure 3.9 are shown in Figure 3.10. The results were repeated to show a closer view of the results in order to easily compare the results of the present study with that of Swanson (2008).

Figure 3.10 shows that listener S3 was able to pitch rank the stimuli in the expected order using the right ear. Figure 3.10 also shows that listeners S25 and S20 were mostly able to rank the stimuli in the expected pitch rank order. The smaller cumulative d’ values that were observed for the other listeners suggested that there was little variation in pitch between the different stimuli. It is assumed that smaller variations in pitch would make it more difficult for listeners to pitch rank the stimuli in the expected order. One listener, S19, ranked the stimuli in almost exactly the opposite order of the expected order.

Some of the cumulative d' results found by Swanson (2008) are presented in Figure 3.11. These results were compared to the results of the present study shown in Figure 3.10. The cumulative d' values for the data of Swanson (2008) showed that all three listeners who participated in that study were able to order the stimuli in the expected pitch rank order.

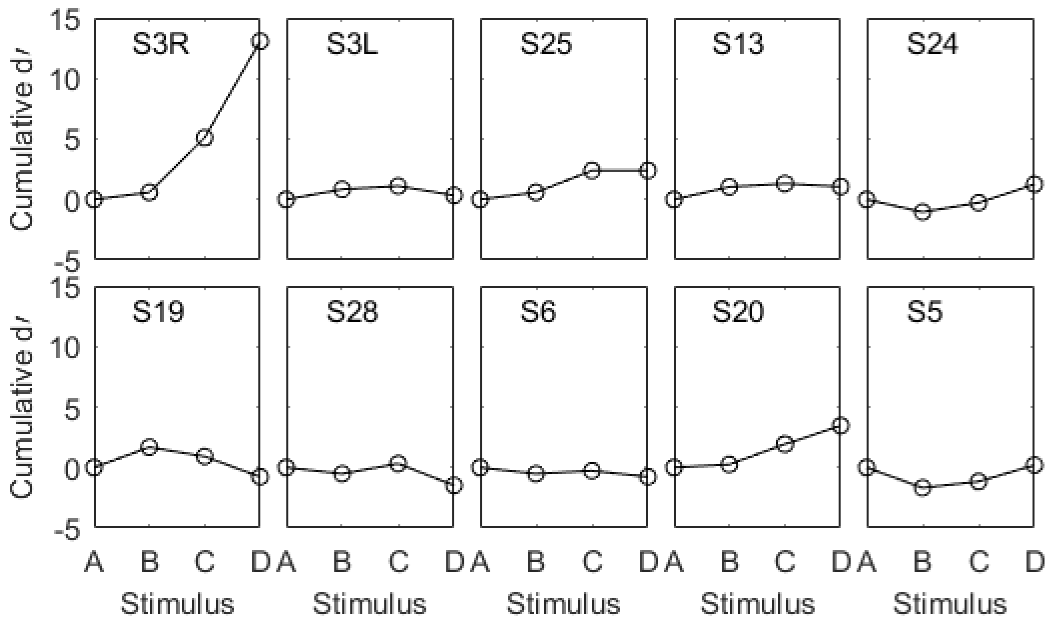


Figure 3.10. Cumulative d' values for experiment 1 of the different listeners.

The cumulative d' values of the two stimulating electrodes ranged between 2 and 8. Figure 3.10 shows that only a third of the 10 listeners tested in the present study could pitch rank all the stimuli in the expected order using the same stimulation parameters as Swanson (2008). Listener S3 could achieve a perfect rank order with her right ear with a cumulative d' of 13.08. The cumulative d' values of the other two listeners (listener S25 and listener S20), who were able to achieve a perfect rank order were 2.39 and 3.46 respectively. The difference between the results of the present study and those of Swanson (2008) is discussed in Section 3.3.

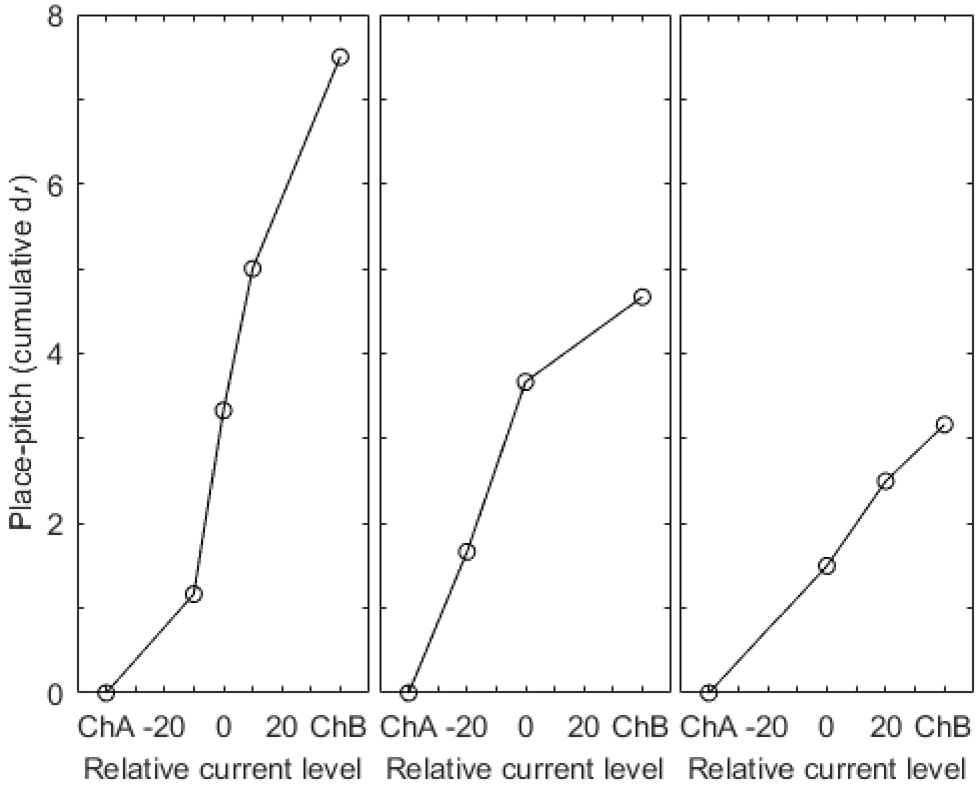


Figure 3.11 Cumulative d' results of three listeners tested by Swanson (2008) were read from the graphs of Swanson (2008) and replotted here. The relative current level on the x-axis works the same as the stimuli of the present study. ChA is the same as stimulus A of the present study and ChB is the same as stimulus D of the present study. The stimulus for which the cumulative d' is shown at, for example, a relative current level of -20 is similar to stimulus B of the present study. In this example 20 CUs are subtracted from the amplitude of the more basal electrode rather than 15 CUs as in the present study.

3.2.4 Statistical analysis

The underlying hypotheses in these experiments was that if a current steering effect could be achieved in the listeners during the pitch ranking experiments, they would always be able to rank the stimuli in the expected order. Apart from the pitch ranking results, the percentage of repetitions to which the response of the listener was as expected (assuming an effective current steering effect) could also be calculated. As mentioned earlier, the expected order from low to high pitch was assumed to be stimuli A, B, C, and D. This would mean that in order for a listener to achieve a percentage of 100% of correct responses, this listener would have to (during each repetition) rank stimulus D higher than A, B and C; the listener would have to rank stimulus C higher than A and B and the listener would have to rank stimulus B higher than A. The percentage of correct (i.e. according to expectation) responses is shown for each experiment of each listener in Figure 3.12.

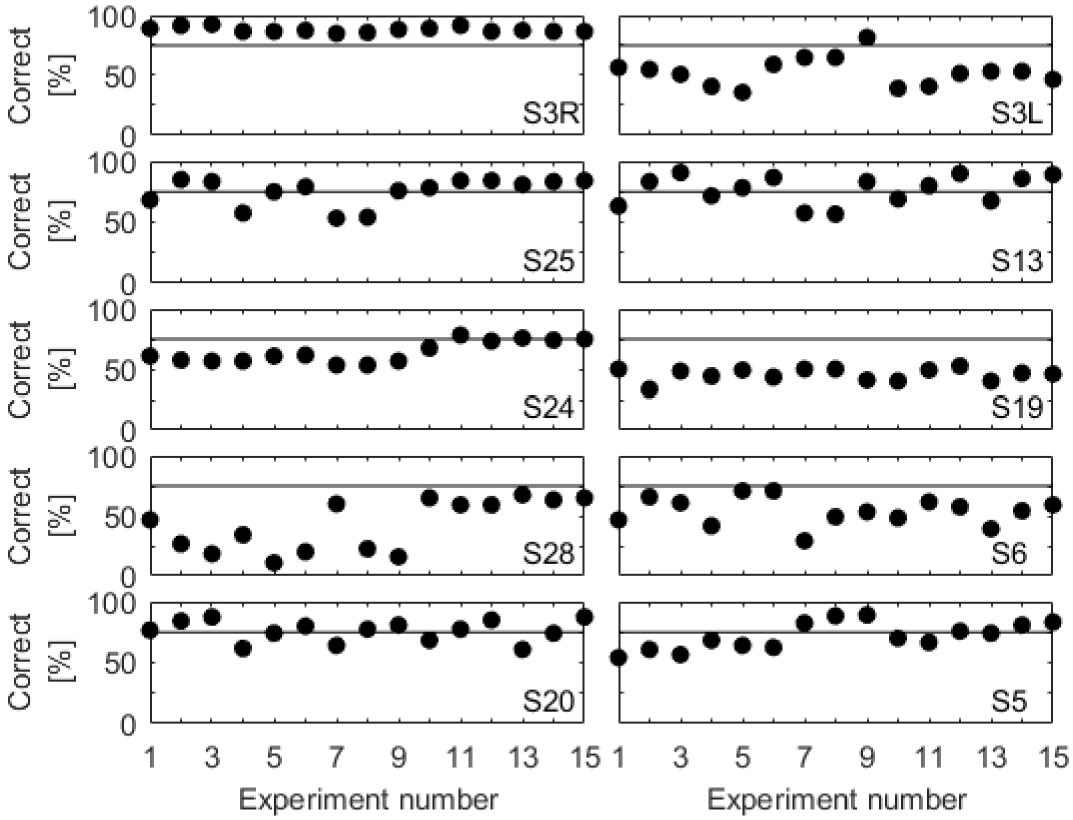


Figure 3.12. Percentage of correct responses (according to the hypothesis) during the pitch ranking experiments of each experiment for each ear.

In Figure 3.12, 50% is the chance performance level. If the listener achieved 100%, it means that the listener responded as expected in that particular experiment. 0% means that the listener always indicated that the opposite stimulus from the expected one was higher in pitch. The solid horizontal line in each graph indicates 75% correct.

The percentage correct results shown in Figure 3.12 were used to conduct a statistical analysis to test if listeners could rank the pitch of stimuli, created to achieve current steering with sequential stimulation, according to expectation. The statistical analyses also tested whether any of the different stimulation parameters (pulse width, stimulation rate or electrode separation) had a significant effect on the pitch ranking results.

3.2.4.1 Testing for achievement of a current steering effect using sequential stimulation

The percentage correct results in Figure 3.12 was used to test whether a current steering effect had been achieved with sequential stimulation for each of the listeners. A t-test was used to determine if each listener did significantly better than chance in the pitch ranking experiments. That is, a t-test was carried out to determine if each listener obtained an average correct percentage that was significantly higher than 50% across the 15 experiments. It was therefore assumed that the percentage correct values across the 15 experiments was drawn from a normal distribution and it was tested whether these values were larger than chance in a statistically significant way. The statistical test results are given in Table 3.6.

Table 3.6 Statistical results of the t-test for each listener.

Listener number	Statistical result
Listener S3R	$t(14)= 64.002, p<0.0005$
Listener S25	$t(14)= 8.444, p<0.0005$
Listener S13	$t(14)= 8.845, p<0.0005$
Listener S24	$t(14)= 6.126, p<0.0005$
Listener S20	$t(14)= 11.317, p<0.0005$
Listener S5	$t(14)= 7.580, p<0.0005$
Listener S3L	$t(14)= 0.994, p=0.337$
Listener S6	$t(14)= 1.261, p=0.228$
Listener S28	$t(14)=-1.384, p=0.188$
Listener S19	$t(14)=-3.254, p=0.006$

Six of the listeners, S3R, S25, S13, S24, S20 and S5, had a percentage correct score that was statistically significantly higher than 50%. On average, these listeners scored above chance in the 15 experiments (seen across experimental conditions, but not necessarily in each individual experiment). Three listeners, S3L, S6 and S28, scored close to chance. Listeners S3L and S6 scored higher than 50% across all the experiments, but not statistically significantly so. The percentage correct score of listener S28 was lower than 50%, but not significantly so. Lastly, the percentage correct score of listener S19 was statistically significantly lower than 50%, which means that this listener mostly ranked the stimuli in the opposite order from the expected order.

Since six of the listeners scored above chance, it can be said that 60% of the listeners ranked the stimuli in the expected order when the average was calculated over all the experiments of a specific listener. This means that, considering the average over all the experiments for each listener, a current steering effect could be achieved in 60% of the listeners. This does not mean that each of these listeners could rank the stimuli in the expected order irrespective of the stimulation parameters that were used during each of the different experiments. 75% correct was set as benchmark to determine if a current steering effect could be achieved for the different listeners for each of the different experiments. Table 3.7 shows the listeners and the experiments for which the listeners scored 75% correct or higher.

Table 3.7 Listeners and the experiments for which these listeners scored 75% correct or above in the pitch ranking task.

Pulse rate (pps)	**Pulse width (µs)**	**Electrode separation distance (number of electrodes)**	**S1R**	**S1L**	**S2**	**S3**	**S4**	**S8**	**S9**
1776	25	0	✓					✓	
1776	25	1	✓		✓	✓		✓	
1776	25	2	✓		✓	✓		✓	
888	25	0	✓						
888	25	1	✓		✓	✓		✓	
888	25	2	✓		✓	✓		✓	
200	25	0	✓						✓
200	25	1	✓					✓	✓
200	25	2	✓	✓	✓	✓		✓	✓
1776	75	0	✓		✓				
1776	75	1	✓		✓	✓	✓	✓	
1776	75	2	✓		✓	✓		✓	✓
1776	132	0	✓		✓		✓		
1776	132	1	✓		✓	✓	✓	✓	✓
1776	132	2	✓		✓	✓	✓	✓	✓

All the listeners who did statistically better than chance scored higher than 75% in at least a few of the experiments. Listener S3 was the only listener who scored above 75% irrespective of the stimulation parameter set when she used her right ear. The effect of the different stimulation parameters used during the different experiments is analysed in more detail in the following section.

3.2.4.2 Testing the effect of the different stimulation parameters on pitch ranking

A multilevel model was used to assess the effect of the different stimulation parameters (pulse rate, pulse width and electrode separation distance) as well as the effect of the variable “listener” on the pitch ranking results. Multilevel models are typically used for clustered data, grouped data or data with a hierarchical organisation, but they are also used for repeated measures of multivariate responses within individuals (Field, 2009). A two-level model was used to analyse the data of the present study; the listener at the one level and the stimulation parameters or experiments at the other level.

The multilevel model can consider variability at both the stimulation parameter and the listener level (Field, 2009). Because multilevel models consider variability at all levels, a multilevel model would appropriately compare stimulation parameters to between-listener variations rather than comparing across the measurements in the same listener and treating the data as independent.

Multilevel models allow several sources of random variation, for example variation between listeners and variation within listeners (Field, 2009). A multilevel model can account for random variation by including random effects to the model. Random effects were included for the "listener" variable. The random effects included in the statistical model will account for unobserved listener characteristics that affect the outcomes of the different experiments. It is these unobserved variables that may lead to correlation between outcomes for the different experiments (or stimulation parameters) from the same listener.

Multilevel models allow the creation of a correlation structure for the data, for example the model can be designed to account for correlation patterns of repeated measures. Since different experiments were carried out for the same person, the data of the present study were considered as repeated measures data. The use of repeated measures means that there may be correlations between the different experiments of the same person, because of the unobserved listener characteristic mentioned earlier. Because the measurements were close together in time, there would be more correlation than if they were widely separated in time. The multilevel model allows one to give some structure to the correlation between the repeated measures.

General linear models assume that all observations are independent. The effects in these models are described as fixed effects to differentiate them from the random effects that can be included in multilevel models. Fixed effects can also be included in multilevel models. For the present study, the pulse width, pulse rate and electrode distance were considered as fixed effects.

Multilevel models can be used even if some data are missing (Field, 2009), which is an advantage for the present study, since not all the combinations (of the different pulse widths, pulse rates and electrode distances) were tested. Repeated measures analysis of variance (ANOVA) was also considered for the analysis, but would only have been suitable if the data had been more complete.

An overall multilevel model analysis, which included all the data of all the listeners, was carried out to show the effect of the different stimulation parameters when “listener” was also considered as one of the variables. An analysis was also carried out for each individual ear to analyse the effect of the different stimulation parameters when only that ear was considered.

Multi-listener analysis (overall analysis)

The multi-listener analysis, consisting of all the data of all the listeners, showed that considering the fixed effects in the model, the variable "listener" had a statistically significant effect on the results, with $F(1, 9.749)=190.109$, $p<0.0005$. The analysis also showed that the distance between the stimulating electrodes had a statistically significant effect on the results, with $F(2, 89.971)=6.760$, $p=0.002$. The pulse rate and the pulse width had no statistically significant effect on the percentage correct results across all the listeners. This does not mean that these parameters will not have a statistically significant effect on the percentage correct results of specific listeners. The effect of pulse rate, pulse width and electrode separation distance on the percentage correct results of each specific listener was tested in the following section.

A pulse rate of 1776 pps, a pulse width of 132 μs and an electrode separation distance of three electrodes were the reference or the baseline with which the effect of changing these parameters was compared. The estimate of fixed effects showed that a fixed intercept value of 72.38 represents the mean percentage correct score at the baseline. The model showed that the intercept for an electrode separation distance of one electrode is 72.38 - 6.99 = 65.39 and that this is significantly lower than the intercept for an electrode separation distance of three electrodes ($t(91.289)=-3.674$, $p<0.0005$; the 95% confidence interval for the difference is 3.21% to 10.77%). The confidence interval means that the model predicts, with 95% confidence, that if the electrode distance is decreased from three electrodes to one electrode, the percentage correct score will decrease by 3.21% to 10.77%.

Similar to the above-mentioned results it was seen that, although not significantly so, an electrode separation distance of two electrodes had a lower intercept than three electrodes, but a higher intercept than one electrode. The results also showed that, although not significantly so, the intercept decreased as the pulse rate decreased and that the intercept decreased as the pulse width decreased. Percentage correct results improved significantly when the electrode separation distance increased from one electrode to three electrodes. None of the other changes in any of the parameters (i.e. changes in pulse rate, changes in pulse width or an increase in electrode separation distance from two electrodes to three electrodes) had a significant effect on the percentage correct results.

Pulse rate, pulse width and electrode separation distance were all classified as fixed effects. As mentioned before, the random effects between listeners due to unobserved listener characteristics, and the random effects within listeners due to repeated measures were also considered with the model. The random effects are considered in a result referred to as the estimates of covariance parameters. While the fixed effects were estimates of the mean parameter, estimates of covariance parameters are estimates of variance parameters. The intercept variance of this model was estimated as 316.95, so the estimate of the standard deviation was 17.8. This tells one, according to the empirical rule (Rumsey, 2007), that for any given stimulation parameter set, e.g. the baseline parameter set with mean intercept of 72.38, the individual subjects will have “personal" intercepts that are up to 17.8 higher or lower than the group average about 68% of the time, and up to 35.6 higher or lower about 95% of the time. The null hypothesis for the “listener” parameter is a variance of zero, which would indicate that a random effect is not needed. The Wald Z test statistic was used to test this hypothesis. Here the null hypothesis was rejected (Wald Z=1.81, p=0.07 ($p < 0.1$)) and it was concluded that a random intercept was needed. This suggests that there are unobserved listener characteristics or variables for each listener that raise or lower their performance in a way that appears random because the value(s) of the missing explanatory variable(s) are unknown (Seltman, 2012).

The model showed that the residual covariance parameters were statistically significant (estimate of covariance due to repeated measures = 112.47, Wald Z= 6.307, p< 0.0005). The intercept variance, which is larger than the residual covariance, suggests that most of the variability unaccounted for by the fixed effects is due to between-listener variation. Since the uncontrollable differences between listeners had the largest effect, a person-specific analysis was also carried out for each listener. This analysis is discussed in the following section. The detailed results of the statistical model discussed in this section were tabulated and are provided in Appendix C.

Individual analysis

A multilevel model analysis was carried out for each individual ear. This section focuses on the results of the fixed effects, since the aim of this section was to determine the effect of the different stimulation parameters on the results of each listener. Table 3.8 presents a summary of the statistically significant results of each listener. More detailed tables with estimates of fixed effects, F, t and p values are given in Appendix C.

None of the parameters had a statistically significant effect on the percentage correct results of listener S19. This observation was expected, since Figure 3.7 showed that the listener was almost never able to rank the stimuli in the expected order. The t-test in Section 3.2.4.1 showed that more often than not, this listener ranked the stimuli in exactly the opposite order than what was expected. Figure 3.12 showed that the listener almost always scored a percentage correct score close to chance level. Further discussion of these observations follows in Section 3.3.2.

The pulse rate and the pulse width had a significant effect on the percentage of correct results of both the right and the left ear of listener S3. This was an interesting observation, since Figure 3.12 showed that on average this listener performed much better during pitch ranking tasks when she was listening with her right ear compared to when she was listening with her left ear.

The test of fixed effects showed that the pulse width had a statistically significant effect on the percentage correct results of listeners S3, S24, S28, S20 and S5. The estimate of fixed effects showed that compared with when a stimulation pulse width of 25 μs was used for stimulation, the percentage correct score of listeners S24, S28 and S5 was statistically significantly higher when the higher pulse width of 132 μs was used. Similarly, it was observed that, compared with when a stimulation pulse width of 132 μs was used for stimulation, the percentage of correct scores of listeners S3R, S6 and S20 was statistically higher when a stimulation pulse width of 25 μs was used.

Table 3.8 Summary of the statistically significant results of each listener for the multilevel model analysis.

Listener	Test of fixed effects			Estimates of fixed effects					
	Pulse rate	Pulse width	Electrode distance	Pulse rate		Pulse width		Electrode distance	
				200 pps	888 pps	25 µs	79 µs	1	2
3R	✓	✓		--	-	++	+		
3L	✓	✓		+	-			(-)	--
25	✓		✓	--	-			--	(-)
13	✓		✓	--	(-)			--	-
24	✓	✓		-	+	--	(-)		
19									
28		✓	✓			--	(-)	++	(+)
6	✓		✓	-	(+)	++	(+)	-	(+)
20	✓	✓	✓	-	--	++	(+)	--	-
5	✓	✓		++	+	--	-	--	(-)

Key for Table 3.8	
Symbol	**Description**
✓	Indicates that the parameter had a statistically significant effect on the percentage correct values.
(-)	Indicates that the intercept for that parameter is lower than the intercept of the baseline or reference parameter, but not significantly so. Thus, using this parameter will decrease, although not significantly so, the percentage correct results compared to the baseline parameter.
-	Indicates that the intercept for that parameter is significantly lower than the intercept of the baseline or reference parameter. Thus, using this parameter will significantly decrease the percentage correct results compared to the baseline parameter.
--	Indicates that the intercept for that parameter is significantly lower than the intercept of the baseline or reference parameter, and the lowest of the three variations of the parameter. Thus, using this parameter will result in the worst percentage correct results of the three possible variations of the specific parameter that was tested.

Key for Table 3.8 continues	
Symbol	**Description**
(+)	Indicates that the intercept for that parameter is higher than the intercept of the baseline or reference parameter, but not significantly so. Thus, using this parameter will increase, although not significantly so, the percentage correct results compared to the baseline parameter.
+	Indicates that the intercept for that parameter is significantly higher than the intercept of the baseline or reference parameter. Thus, using this parameter will significantly increase the percentage correct results compared to the baseline parameter.
++	Indicates that the intercept for that parameter is significantly higher than the intercept of the baseline or reference parameter, and the highest of the three variations of the parameter. Thus, using this parameter will result in the best percentage correct results of the three possible variations of the specific parameter that was tested.

According to the test of fixed effects, the electrode separation distance had a statistically significant effect on the percentage correct results of listeners S25, S13, S28, S6 and S20. The estimates of fixed effects showed that listener S28 performed statistically significantly better (in the sense of having a higher percentage correct score) when the electrode separation distance was equal to one electrode. All the other listeners affected by the electrode separation distance performed statistically significantly better as the electrode separation distance increased.

Interestingly, the estimate of fixed effects shows that for some listeners increasing the pulse rate resulted in a significantly higher percentage of correct scores, while for other listeners decreasing the pulse rate had the same effect. This same observation was made when pulse widths were increased or decreased. As discussed above, an increase in electrode separation distance on the contrary seemed to result in a statistically higher percentage of correct scores for most of the listeners. This explains why the multi-listener analysis in the previous section, which considered the data for all the listeners, showed that electrode separation distance had a statistically significant effect on the percentage correct scores while the other two stimulation parameters did not.

The test of fixed effects showed that the pulse rate had a statistically significant effect on the percentage correct pitch ranking results of all the listeners except for listener S19 and listener S28. This means that the pulse rate had a statistically significant effect on the percentage correct results of all the listeners who scored higher than 50% in the statistical tests carried out in Section 3.2.4.1, irrespective of whether the score was significantly higher or not.

Considering the estimates of fixed effects in Table 3.8, it is seen that six of the CI users (listeners S3R, S25, S13, S24, S20 and S6) mostly performed better in the pitch ranking task at higher pulse rates. Listener S3L and listener S5 performed best when the pulse rate was 200 pps. Considering the profile and background of the users in Table 3.1, it is seen that the stimulation rate in the everyday MAP of the implant of most users is higher: between 900 pps and 1776 pps. However, the simulation rate of the implant of listener S5 is 250 pps, and the stimulation rate of the original implant in the left ear of listener S3 was 240 pps. It is conceivable that the stimulation rate affects the performance of the listeners, because the auditory centres in the brain have adjusted to a certain stimulation rate after years of implant use. A statistical analysis was conducted to test this hypothesis and is presented and discussed in the following section.

3.2.4.3 Testing effect of stimulation rate of CI of users on pitch ranking results

A multilevel model was used to determine the effect of the stimulation rate indicated in the clinical MAP of the different CI users, as well as the interaction between the stimulation rate in the clinical MAP and the stimulation rate used in the different experiments on the percentage correct results. A new parameter (stimulation pulse rate on clinical MAP of CI user) was added to the multi-listener model discussed in Section 3.2.4.2.

Adding the new parameter to the multilevel model resulted in a model that improved the fit to the data. Subtracting the log-likelihood of the new model from the old model supports this statement. It was found that

$$x^2_{Change} = (-2Log - Likelihood_{old})|(-2Log - Likelihood_{New}) \\ = 1127.218 - 1011.331 = 115.887 \tag{3.5}$$

and

$$df_{Change} = difference\ between\ number\ of\ parameters\ in\ each\ model \\ = 24 - 12 = 12. \tag{3.6}$$

The critical values for the chi-square statistic with 12 degrees of freedom are 21.03 ($p<0.05$) and 26.22 ($p<0.01$); therefore, this change is highly significant.

This analysis showed that when all the listeners were considered together, as previously stated (in the multi-listener analysis section of Section 3.2.4.2) the electrode separation distance had a statistically significant effect on the percentage correct results, but in this model $F(2, 99.914)=7.185$, $p=0.001$. When the clinical MAP stimulation rate of the implants of the CI users was added to the model, the analysis shows that the stimulation rate used in the different experiments had a statistically significant effect on the percentage correct results with $F(2, 51.368)=3.986$, $p=0.025$. The original stimulation rate of the clinical MAP did not directly have a statistically significant effect on the percentage correct results $F(4, 5.095)=1.223$, $p=0.405$. However, the interaction between the original stimulation rate of the clinical MAP and the stimulation rate used in the experiments did have a significant effect on the percentage correct results with $F(8, 47.134)=6.374$, $p<0.0005$. The results of this statistical analysis support the hypothesis that the original stimulation rate of the clinical MAP might have an impact on the performance of the CI users in the current steering experiments.

3.3 SINGLE ELECTRODE PITCH RANKING EXPERIMENTS

Section 3.2.3 and Section 3.2.4 showed that while a current steering effect was achieved in all the listeners who participated in the study of Swanson (2008), a current steering effect was achieved in only 60% of the listeners who participated in the present study. The question surfaces why some listeners benefitted from current steering with sequential stimulation, while others did not. A natural assumption would be that the difference lies in the anatomical differences between users and the position of the electrode in the cochlea of each listener. Another factor that might have an impact is the time that the users had to get used to electric hearing, but this factor should assumedly not affect the present study. All the listeners who participated in the study had had enough time to adapt to electric hearing before they participated in this study.

A simple experiment that could serve as the first step to answer the question of why some listeners benefitted from current steering with sequential stimulation, while others did not, was carried out. Theoretically listeners would not be able to pitch rank current-steered stimuli if they could not distinguish between the pitch of different electrodes, because the current-steered stimuli used in the present study were created with the aim to create pitches between those elicited by adjacent electrodes. An electrode pitch ranking experiment was carried out with a small number of listeners to test this hypothesis. The experiment consisted of a subgroup of the listeners who participated in the main current steering experiments. Only the electrodes surrounding and including the electrodes used in the main current steering experiments were included in this experiment.

3.3.1 Method

Three listeners who had difficulty ranking the pitch of the stimuli used in the present study, namely listeners S19, S28 and S6, as well as two listeners who were able to perform the pitch ranking task effectively, namely listeners S20 and S5, participated in the electrode pitch ranking experiments.

Electrodes 10 to 15 were pitch ranked in this experiment. A single electrode was stimulated at a time, using the stimulation parameters of experiments 1 to 3 in Table 3.2. A variation on these stimulation parameters was used for listener S5. She participated in a second electrode pitch ranking experiment where the single electrodes were stimulated using the stimulation parameters of experiments 7 to 9. The second electrode pitch ranking experiment was added for this listener, because she performed noticeably better in experiments 7 to 9 than in experiments 1 to 3 during the main pitch ranking experiments of this study, reported on in Section 3.2. Doing both variations of the electrode pitch ranking experiments could possibly support or explain the results observed during the main pitch ranking experiments.

The stimuli of these experiments were loudness-balanced in the same manner as the stimuli of the experiments in Section 3.2. Loudness roving was added to the stimulation amplitudes of the stimuli, as explained in Section 3.2.1.3. After loudness balancing had been carried out and loudness roving had been added, the listener was asked to pitch rank the stimuli of individual electrodes.

For the electrode pitch ranking a 500 ms stimulus was applied to a randomly selected electrode between electrode 10 and electrode 15. The stimulus was followed by 500 ms silence and another 500 ms stimulus was applied to another random electrode between electrode 10 and electrode 15 (not the same as the electrode of the first stimulus). The listener was then asked to choose which one of the two stimuli was higher in pitch. Since only the electrode pitch rank order was of interest, and not the perceptual distance between the electrodes, the midpoint comparison procedure was used to determine the electrode pitch rank (Long, Nimmo-Smith, Baguley, O'Driscoll, Ramsden, Otto, Axon and Carlyon, 2005).

3.3.2 Results and analysis of results for the single-electrode pitch ranking experiments

The results obtained for the single-electrode pitch ranking experiments for each of the participating listeners are shown in Figure 3.13. Considering the Greenwood equation (Greenwood, 1990) and the theories stating that the cochlea is tonotopically organised, it was expected that the stimuli on electrodes closer to the base (electrode 10) would be ranked highest in pitch. Likewise, stimuli on electrodes closer to the apex (electrode 15) was expected to be ranked lower in pitch.

The mean electrode pitch rank positions of the six ranked electrodes of listener S19 almost oppose the expected order. It could be an indication that the listener was unsure about the pitch ranking tasks and perhaps indicated which stimulus was lower, rather than higher, in pitch. The large standard deviation from the mean of this listener suggests that this was probably not the case. The large standard deviation from the mean appears to indicate that the listener confused the pitch of the different electrodes. The pitches of electrodes 10 to 14 of this listener were all more or less ranked at the same pitch position. Only electrode 15 was ranked higher in pitch. It is clear that this listener was unable to do electrode pitch ranking, and would therefore probably not have been able to pitch rank current-steered stimuli. This hypothesis is supported by the pitch ranking results of the current-steered stimuli of this listener seen in Figure 3.12.

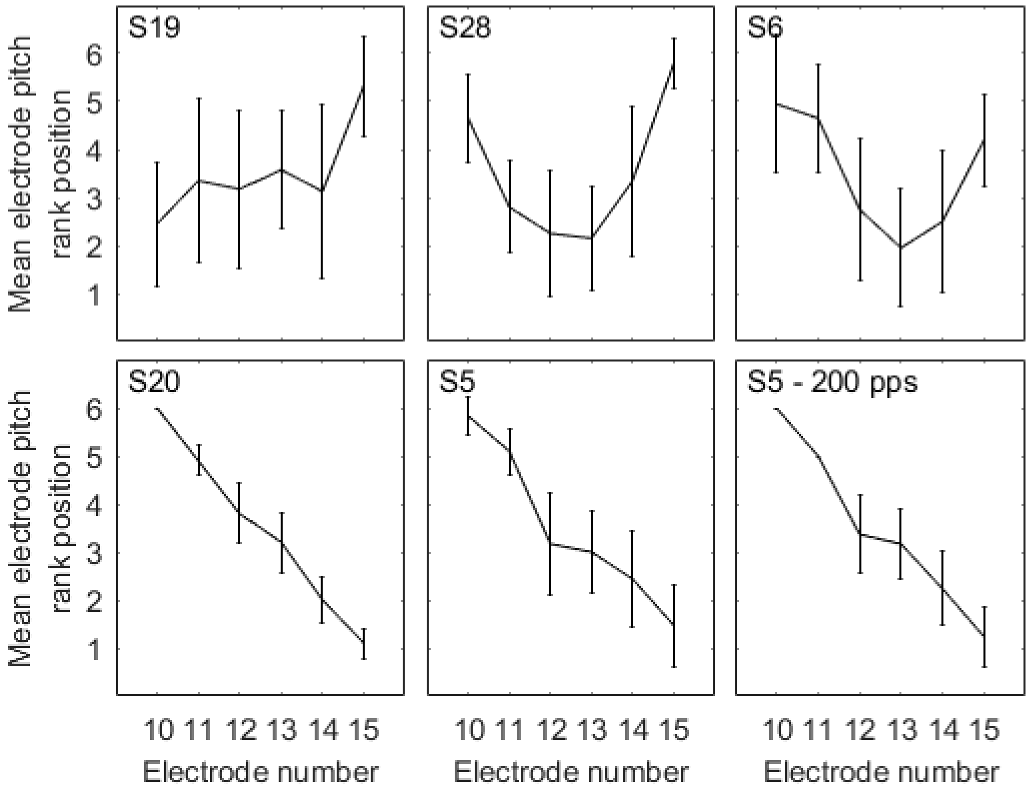


Figure 3.13 Electrode pitch ranking results. A stimulation rate of 1776 pps was used in all the experiments, except for the one labelled S5 – 200 pps, where a stimulation rate of 200 pps was used. Electrode 10 was located more towards the base compared to electrodes with higher numbers.

The u-shape of the mean electrode pitch rank orders of listener S28 and listener S6 suggests that two different stimuli were often ranked at almost the same pitch. The large standard deviation in these graphs shows that the pitch, created by numerous of the tested electrodes, might result in the listener perceiving almost exactly the same pitch irrespective of which electrode was being stimulated.

Pitch ranking the current-steered stimuli might require a listener to be able at least to distinguish between the pitch of electrode 11 and 12 or electrode 11 and 13 or electrode 11 and 14. For the remainder of this discussion and for the sake of simplicity, electrodes 11 and 12 will be referred to as electrode pair 1, electrodes 11 and 13 will be referred to as electrode pair 2 and electrodes 11 and 14 as electrode pair 3.

When any of the electrode pairs of listener S28 is considered in Figure 3.13, it is seen from the standard deviation from the means that there is almost no difference between the pitch of the two separate electrodes in any of the electrode pairs. This may explain the data in Figure 3.12, which also shows that this listener was unable to distinguish between the pitches of the stimuli created by using current steering. Since the listener found it difficult to distinguish between the different electrodes in an electrode pair, it is understandable that she would struggle to pitch rank stimuli designed to be intermediate to the electrodes of the electrode pairs.

The observations made for listener S6 were similar to those of listener S28, but showed a few new, interesting observations. The mean electrode pitch rank position of electrode 11 was considerably higher than those of electrodes 12 to 14. The mean electrode pitch rank position of electrodes 12 to 14 was very similar, especially for electrodes 12 and 14. Because of the large standard deviation from the mean, there is a rather large overlap between the pitch rank of the two electrodes of electrode pair 1 and electrode pair 3, which is expected to indicate that there is no significant difference in pitch. Even with the large standard deviations, there is no overlap in the standard deviations of the pitch rank positions of the electrodes of electrode pair 2, which may indicate a significant difference in pitch (although this was not tested statistically). It was expected that it would be easier for this listener to distinguish between the pitch created by stimulation on the electrodes of electrode pair 2 than to distinguish between the pitch created by stimulation on the electrodes of the other two electrode pairs.

As previously discussed, d' can provide an estimate of the perceptual distance in pitch between stimuli. In addition to (3.3) and (3.4), d' can also be calculated by

$$d' = \frac{\mu_X - \mu_Y}{\sqrt{\frac{1}{2}\,(\sigma_X^2 + \sigma_Y^2)}}, \tag{3.7}$$

where μ_X and σ_X, and μ_Y and σ_Y are the mean and standard deviation of the pitch of stimulus X and the pitch of stimulus Y. Calculating d' between the pitches produced by the electrodes in each electrode pair resulted in $d'_{pair1} = 1.4$, $d'_{pair2} = 2.3$ and $d'_{pair3} = 1.6$.

The d' values support the notion that it would be easier for listener S6 to distinguish between the pitch created by stimulation on the electrodes of electrode pair 2 than to distinguish between the pitch created by stimulation on the electrodes of electrode pairs 1 and 3. This expectation was supported by the results in Figure 3.12. The results of listener S6 of the first three experiments in Figure 3.12 showed that the listener found it easier to pitch rank the stimuli between electrode pair 2 (experiment 2) than the stimuli between electrode pair 1 or 3 (experiment 1 and experiment 3 respectively). These results suggest that there is a relationship between the ability of the listener to pitch rank individual electrodes and the ability of the listener to pitch rank current-steered stimuli.

Because of the tonotopic arrangement of the cochlea, the shape of the graphs of listener S20 and listener S5 was exactly as expected for a listener who can easily discriminate between the pitch created by different electrodes. For these listeners, there was no overlap in the standard deviation of the electrode pitch rank positions between the pitches created by the electrodes of the different electrode pairs. The standard deviation from the mean was particularly small for listener S20, which might explain why she was able to perform so well in the experiment of which data is shown in Figure 3.12. Listener S20 participated in an electrode discrimination experiment conducted by Venter (2015). Her electrode discrimination ability for any given electrode was always 100% or close to 100% correct. This is consistent with her ability to pitch rank stimuli accurately on different electrodes.

The electrode pitch rank positions of electrodes 12 to 14 are very similar for listener S5, even more so because of the larger standard deviation at 1776 pps than at 200 pps. However, there is no electrode place pitch position overlap between electrode 11 and any of the electrodes mentioned. As mentioned, it was expected that listeners should be able to distinguish between pitches of stimuli on different electrodes before they would be able to distinguish between the pitch of stimuli created using current steering. Based on this hypothesis and the results of listener S5, the listener should be able to perceive the pitch of intermediate pitches, irrespective of whether a stimulation rate of 1776 pps or 200 pps is used. Results in Figure 3.12 do not support this statement, which raises the question why this listener could do pitch ranking of current-steered stimuli at 200 pps but not at 1776 pps when she was able to successfully do electrode pitch ranking at both stimulation rates. One could argue that it is explained by the smaller standard deviations from the mean electrode pitch rank position at 200 pps than at 1776 pps. Yet, the difference between the size of the standard deviation at 1776 pps and 200 pps is too small in comparison with the difference in performance results observed between experiments 1 to 3 and experiments 7 to 9 in Figure 3.12 for this argument to stand.

A stronger argument could be that the listener could pitch rank stimuli created by current steering at 200 pps but not at 1776 pps, owing to the familiarity of the stimulation rate. This hypothesis is supported by the results of the statistical analysis carried out in Section 3.2.4.3, because the implant of this listener usually stimulates at 250 pps. The analysis carried out in Section 3.2.4.3 showed that the original stimulation rate of the clinical MAP might have an impact on the performance of the CI users in the current steering experiments.

Electrode pitch discrimination tasks only involved simple stimuli, while current steering involved complex stimuli. Combining the stimulation of two electrodes and asking listeners to distinguish between complex stimuli might require them to listen to other, more complex features. Perhaps these features are more prominent at stimulation frequencies to which the auditory processing centres of the brain are adapted, or masked by unfamiliar stimulation frequencies. It is possible that with practice and training this listener might be able to perform better in pitch ranking tasks of stimuli, created with the aim of achieving current steering effects, at a stimulation rate of 1776 pps (Hassan, Hegazi and Al-Kassaby, 2013, Looi, Wong and Loo, 2016).

Considering the results in Figure 3.13, it seems as if the electrode pitch ranking ability of listeners are strongly influenced by factors other than just the stimulation parameters that are used. Some of these other influential factors could include the position of the electrodes relative to the nerves or the number of remaining nerve fibres (Loizou, 1999). An important note is that in some cases it might be easier to create current steering effects between electrodes situated closer to one another as opposed to electrodes with larger spacing. This statement is based on two arguments. Firstly, it is possible that neural interaction will not occur when electrode spanning is carried out with sequential stimulation, which means that there will be no current steering effect. The second reason is the possibility of cross-turn stimulation (Frijns, Briaire and Grote, 2001, Macherey and Carlyon, 2014). One interpretation is that the u-shape of the curves observed in the results of listener S28 and listener S6 in Figure 3.13 was a result of cross-turn stimulation.

Although this was a small sample of listeners, it appears overall that listeners are only able to perform pitch ranking of stimuli, created with the aim to achieve current steering effects, if they can also successfully do single electrode pitch ranking. This may also suggest that the listeners who are able to pitch rank current-steered stimuli, have narrower current distribution patterns away from the electrodes. The standard deviation from the mean electrode pitch rank position gives a good indication of the ability of the listener to do both electrode pitch ranking and pitch ranking of more complex current-steered stimuli.

3.4 DISCUSSION

Numerous studies have shown that a current steering effect can be achieved using simultaneous stimulation of two electrodes (Koch *et al*., 2007, Saoji and Litvak, 2010, Snel-Bongers *et al*., 2011, Snel-Bongers, Briaire, Van Der Veen, Kalkman and Frijns, 2013, Wu and Luo, 2013). Various stimulation parameters can be used to achieve a current steering effect with simultaneous stimulation. For example, different stimulation modes, different stimulation amplitudes, different electrode separation distances and different pulse rates (see Figure 1.1). Research has shown that the number of individual pitches perceived between two adjacent electrodes can be increased through current steering when simultaneous stimulation is used.

Only a few studies have investigated the possibility of current steering when sequential stimulation is used (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). These studies also found that intermediate place pitch percepts could be created using current steering. The present study confirmed these findings using alternative methods such as MDS and statistical analysis. The conventional method of using cumulative d' to determine perceptual distance between different pitches was also considered in the present study.

3.4.1 Comparison with other literature

Three other sequential stimulation studies found in literature used cumulative d' values to assess whether the listeners were able to pitch rank stimuli in the order expected when current steering effects were applied (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). Table 3.9 summarises the different stimulation parameters used in the different studies.

Kwon and van den Honert (2006) used d' to determine the perceptual distance between the pitches of the two stimulating electrodes. They calculated the number of discriminable steps (jnds) to determine how many pitches the listener could hear between the two electrodes. Even though the results of the different listeners varied widely, they only reported on the mean number of discriminable steps over all the users, the listener with the lowest mean jnds between the different electrode pairs of this listener, and the listener with the highest mean jnds between the different electrode pairs of this listener. Twelve listeners were tested. The number of jnds differed for all the different listeners. It was reported that most of the listeners who were tested could perceive pitches intermediate to the two stimulating electrodes.

Table 3.9 Summary of the different stimulation parameters used in different studies found in literature.

	Kwon and van den Honert (2006)	**McDermott and McKay (1994)**	**Swanson (2008)**	**The present study**
Pulse rate (pps)	(500-1800) per the clinical MAP of the listener	250	1776	1776
Pulse width (µs)	25	100	25	25
Inter-pulse delay (µs)	8	8	8	8
Delay between pulse on first electrode and second electrode (µs)	19	600	70.4	70.4
Electrode pair	(10, 11)	(16, 17)	(11, 12)	(11, 12)
Stimulation mode	Monopolar	Bipolar (BP+1)	Monopolar	Monopolar
Duration of stimulus (ms)	500	500	500	500
Electrode separation distance (mm)	0.57 (Nucleus contour), 0.75 (Nucleus CI24 straight)	0.75	0.4 to 0.5	0.5

The results of the present study are consistent with the results reported by Kwon and van den Honert (2006). Both studies found that it is possible to create intermediate pitch percepts using current steering and sequential stimulation. Kwon and van den Honert (2006) showed that more than 80% of the listeners who participated in their study could perceive intermediate pitches between stimulating electrodes due to current steering effects created with sequential stimulation. Both studies showed that although current steering effects can be achieved by using sequential stimulation, current steering effects cannot be achieved in all CI listeners.

McDermott and McKay (1994) showed that the five listeners they tested were all able to achieve intermediate pitches at a range of cochlear positions. They stated that in half of the cases, a significantly different pitch could be created intermediate to two adjacent electrodes. This is similar to the 60% of the listeners of the present study who were able to perceive intermediate pitches between stimulating electrodes.

It is somewhat more problematic to compare the present study with that of McDermott and McKay (1994), since the stimulation modes were different. The effects of monopolar and bipolar stimulation on the pitch ranking ability of CI listeners were not tested in this study, but as explained in Section 3.2.1.2, the stimulation mode might have an effect on the effectiveness of current steering. Most modern-day implants use monopolar stimulation and therefore it was decided to carry out experiments using only monopolar stimulation. Both the study of McDermott and McKay (1994) and the present study showed that intermediate pitches can be created between adjacent electrodes for some listeners with certain stimulation parameters.

As discussed in Section 3.2.3, Swanson (2008) also showed that intermediate pitches can be achieved when current steering effects are created with sequential stimulation. Considering the cumulative MDS results in Section 3.2.2, the cumulative d' results in Section 3.2.3 and the statistical analysis in Section 3.2.4.1, the findings of the present study were consistent with the findings shown in literature. It was confirmed that current steering effects can be achieved using sequential stimulation.

The exception was that the studies shown in literature often concluded that most listeners could pitch rank intermediate pitches in an expected order, while the present study found that only some listeners could pitch rank intermediate pitches, using very specific stimulation parameters. A possible reason for this could be that the ability to achieve current steering effects with sequential stimulation is dependent on the stimulation parameters that are used. The effects of different stimulation parameters on the pitch rank ability of CI listeners, presented with current-steered stimuli, were not clear from the cited studies. Psychoacoustic experiments were carried out in the present study to investigate these effects. The key results of these experiments are discussed in Section 3.4.2.

Section 3.3.2 showed that the listeners in the present study who could not pitch rank the two stimulating electrodes could not pitch rank the intermediate pitches either. Electrode pitch ranking gives a good indication of whether a listener will be able to pitch rank stimuli created with the aim of achieving current steering. Swanson (2008) conducted an experiment to test if listeners can pitch rank two adjacent electrodes. He found that all the listeners who achieved a high percentage of correct results in this experiment were also able to pitch rank stimuli created through current steering for the same stimulation parameters as experiment 1 of the present study. The electrode pitch ranking results in Section 3.3.2 support the results of Swanson (2008).

A possible reason for the observations made in Section 3.3.2 might be that the listeners who are able to pitch rank electrodes and current-steered stimuli have narrower current distribution patterns from the electrodes to the nerve fibres. Narrower current distributions would mean that there is less overlap between areas of activated nerve fibres for different stimuli (Padilla, Stupak and Landsberger, 2017). Less overlap between neural populations activated by different stimuli should make it easier to discriminate between the different pitches (Padilla *et al*., 2017).

3.4.2 Effect of the different stimulation parameters on pitch ranking

The stimulation parameters that were tested during the present study to evaluate their potential influence on the effectiveness of current steering included stimulation amplitude, pulse rate, pulse width, the period between stimulation on the first electrode and the second electrode, pulse phase conditions and the distance between stimulating electrodes. Further testing of pulse phase conditions and the stimulation amplitude was eliminated after pilot experiments showed no clear changes, compared to a control experiment, in the pitch ranking performance of CI listeners when either of these stimulation parameters was altered.

There might have been no clear difference between the place pitch ranking results of the listener when spread mode was used compared to when burst mode was used at a rate of 1776 pps, because the time between stimulation on the two electrodes is less important than the fact that the sequential stimulation should take place within the refractory period of the nerves. As explained in Section 3.2.1.2, it appears that a current steering effect cannot be created using spread mode at a stimulation rate of 200 pps. Although the pilot experiments showed that the listener performed slightly worse during pitch ranking of stimuli at a stimulation rate of 200 pps when spread mode was used compared to when burst mode was used, no clear difference in pitch ranking results was observed here either. It may be possible that the effect of burst mode and spread mode at this low stimulation rate was masked by the clear negative effect of the low stimulation rate compared to the higher stimulation rate of the control experiment on the pitch ranking ability of this listener. A different observation might be made if the effect of pulse phase conditions were tested on a listener who performed well at low pulse rates, for example listener S3.

Current steering is usually carried out at the most comfortable loudness levels (Snel-Bongers *et al.*, 2013). Another study showed that listeners demonstrate better place-pitch discrimination at higher stimulus levels (rather than stimuli created at low loudness levels) (Donaldson, Kreft and Litvak, 2005). The pilot experiments of the present study showed that there was no clear change in pitch ranking results when a stimulation amplitude of 100% of the dynamic range was used compared to a stimulation amplitude of 75% of the dynamic range. The loudness of the stimuli might have no effect on the pitch ranking ability of CI listeners, as long as the presented stimuli are clearly audible.

The effects that the other stimulation parameters had on the pitch ranking ability of CI users were analysed using statistical analysis after psychoacoustic experiments had been carried out. The multilevel model presented in Section 3.2.4.2, which included all the listeners simultaneously, showed that the average performance of all the listeners over all the experiments were mostly affected by the factor "listener". This becomes self-explanatory when it is realised that there are many more parameters (including ones that cannot be controlled) that have an impact on the performance ability of each CI user. Some examples are the insertion depth of the electrode (Chatterjee and Shannon, 1998, Loizou, 1999, Laneau and Wouters, 2004, Macherey and Carlyon, 2012), whether the electrode is inserted into the scala tympani or the scala vestibuli (Loizou, 1999, Saoji and Litvak, 2010, Macherey and Carlyon, 2012), the number of remaining auditory nerves (Chatterjee and Shannon, 1998, Loizou, 1999), bone density (Iwasaki, Atsumi, Ocho and Mizuta, 1998), current distribution through the cochlea (Macherey and Carlyon, 2012), and the distance between the electrode contacts and the auditory nerves (Loizou, 1999).

Even though the multilevel model showed that "listener" was the dominating factor in the performance ability of the listeners during the pitch ranking experiments, Section 3.2.4.1 showed that 60% of the listeners in the study could benefit from current steering effects. Using current steering to increase the number of audible pitches for a CI listener is a person-specific solution. Even the 60% who were able to pitch rank stimuli, created with the aim of achieving current steering, could only do so when certain stimulation parameters were used for stimulation. These parameters differed for each listener, again making it a person-specific solution. For example, increasing the stimulation pulse width improved the results of some of the listeners.

Most listeners who were able to distinguish pitches successfully during the current steering experiments performed better when the electrode separation distance was wider. This means that sequential stimulation can also be used for current steering in devices where electrodes are spaced further away from each other (Cochlear, 2012) or when some electrodes do not work anymore (Chung *et al.*, 2010). Using current steering to steer current to nerve fibres where electrodes do not work can be very beneficial because it might prevent the CI listener having to be reimplanted with a working electrode array. Removal of cochlear implants and reimplantation can cause extensive hair cell loss and additional trauma or damage to different areas within the cochlea, including the basilar membrane and osseous spiral lamina (Shepherd, Clark, Xu and Pyman, 1995, Rivas, Marlowe, Chinnici, Niparko and Francis, 2008).

The furthest electrode separation distance tested was three electrodes (1.9 mm apart). It cannot be assumed that the performance of the CI users would continue to improve as the electrode separation distance continues to increase. Especially since sequential stimulation is used, large electrode separation distances might result in the listener hearing two pitches rather than a single pitch. Stimulating with electrodes that are close to one another possibly stimulates mostly overlapping neural populations. Stimulating with electrodes that are further apart will possibly not have similar neural interaction patterns. This might lead to multitone sounds, especially since the populations are stimulated at different times, first with one electrode, then with the other. It is also possible that the listener will still only perceive a single pitch even while the stimulating electrodes are far apart. While sequential stimulation on the two electrodes is applied within the refractory period of the neurons, the brain might still integrate and interpret it as a single stimulus. The effects of electrode spanning (Snel-Bongers *et al*., 2011) when sequential stimulation is used are unclear.

The present implants of listener S3 stimulate at a stimulation rate of 500 pps. Her original implant in her left ear stimulated at a frequency of 240 pps. It was interesting to see that she performed better with her left ear for the experiments that used a stimulation rate of 200 pps. The same was observed for listener S5 who stated that she found it possible to distinguish between the pitches of the different stimuli of experiments 7 to 9, while she found it extremely difficult to complete the other pitch ranking experiments. Her implant usually stimulates at a rate of 250 pps. She too performed better in the experiments with the lower stimulation rates. This observation was very prominent for these two listeners, but the statistical analysis explained in Section 3.2.4.3 showed that this observation could be made for all the listeners.

The statistical analyses showed that the correspondence between the stimulation rate used in the experiment and the stimulation rate indicated on the clinical MAP of the CI user had a significant effect on the results. Listeners performed significantly better in the experiments where the stimulation rate was similar to the stimulation rate indicated on the clinical MAP of the CI listener. It might be because the auditory centres of their brains are used to a certain stimulation rate. Unfamiliar stimulation rates might mask the cues needed to perceive the pitch of current-steered stimuli.

Just as the feedback of listener S5 corresponded with her results, other listeners also provided interesting feedback. Anecdotal listener feedback of other listeners is discussed in the following section.

3.4.3 Anecdotal listener feedback

Some of the listeners gave feedback on their experiences with the experiments. Listener S3 reported that she used to be able to hear very well with her left implant when it was her only implant. She mentioned that after her implant (left) developed a defect and was removed and she was implanted with a new electrode array, her right ear became her stronger ear.

The listener feedback was interesting considering the results. The results of listener S3 showed that, just as she explained, she performs better with her right ear than her left ear. The difference in performance between the two ears might be due to tissue damage or hair cell loss. Hair cell damage and loss often occur when electrodes are removed (Shepherd *et al*., 1995). The basilar membrane and other cochlear structures such as the osseous spiral lamina could also have been damaged when the new electrode was implanted (Shepherd *et al*., 1995). It has been stated that cochlear reimplantation can have negative functional consequences in some patients (Rivas *et al*., 2008). The effects observed in the left ear of this listener may be an example of such a case.

Listener S25 said that he found experiments 10 to 15 much easier than the other experiments. Results showed that listener S25 performed better in the experiments that he found easier.

Two stimuli, hypothesised to represent two pitches, were played to the listeners during the pitch ranking experiment. Listener S19 reported that she sometimes heard three different pitches. This was unexpected, since the time difference between stimulation on the first electrode and the second electrode was within the refractory period of the neurons. The exact cause of this observation is not clear. It could be that there was no neural interaction when the dual-electrode stimulus was applied. This could be because of the specific current pathways, which might cause completely different neural populations to be activated.

3.5 SUMMARY

Through psychoacoustic experiments, this chapter confirmed that current steering effects can be achieved when sequential stimulation is used. In Section 3.2, the experimental results were analysed using numerous methods, including MDS, cumulative d' and statistical analysis, but the findings were uniform. The results of the present study were compared with and supported by other literature, as discussed in Section 3.2.3 and Section 3.4.1

This chapter also investigated the effect of the stimulation parameters on the pitch ranking performance of CI users when stimuli are created with the aim to achieve current steering with sequential stimulation. Statistical analysis showed that the listener is the dominant factor that influences the pitch ranking performance of the CI users. Section 3.2.4.2 did however also show the effect of the different stimulation parameters on each of the listeners. This chapter showed that the use of stimuli created by applying sequential stimulation in a way that will create current steering effects is a person-specific solution, which can be optimised by using appropriate stimulation parameters.

Previous studies have suggested that the pitch observed in response to current steering effects are related to place pitch (Swanson, 2008). The following chapter shows and discusses the comparison between place pitch model predictions and the data measured as documented in Chapter 3.

CHAPTER 4 CURRENT DISTRIBUTION MODEL

4.1 INTRODUCTION

A person-specific current distribution model was developed in MATLAB. The model predicted how the current of stimulating electrodes will distribute through the cochlea to the auditory nerve. The model also predicted the position along the auditory nerve of different features, resulting from electrical stimulation, that may underlie place pitch (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008, Frijns *et al*., 2009, Macherey and Carlyon, 2012, Venter, 2015). The model was based on an existing 3D person-specific volume conduction model (Malherbe *et al*., 2015). This chapter describes the model and shows how the model predictions of different features are related to data measured in Section 3.2. The objective was to find the specific aspect of the current distribution pattern or neural activation pattern that corresponds best to the observed place pitch.

4.2 METHOD

4.2.1 3D person-specific finite element volume conduction model

Three-dimensional person-specific, finite element volume conduction models exist at present for listeners S3, S25 and S13 who participated in the present study (Malherbe *et al*., 2015). The relevant information of these listeners was given in Table 3.1. Current distribution patterns were extracted from 3D person-specific finite element volume conduction models and used to create a MATLAB current distribution model (Malherbe *et al*., 2015). The 3D models were used to determine the current distribution throughout the cochlea and the head of the listener when a specific current was applied to an electrode. Because the model is purely resistive, the potential measured at any place in the cochlea in the model was equal to the resistance along the pathway to the measurement point, if a 1 A current was applied to any of the electrodes in the model. Note that this does not imply that 1 A current can or will ever be used to stimulate an actual electrode; the applied current was simply used to measure the current distribution from the electrodes to the nerve fibres. The current distribution throughout each volume conduction model was used to construct a current distribution model for each listener in MATLAB.

There were two reasons why, in addition to the already existing volume conduction model, the current distribution model was created in MATLAB. Firstly, the MATLAB model was created to ensure time and resource efficiency. Current distribution patterns can be observed and measured directly from the volume conduction model, but every time a certain current level is applied to an electrode the model must be solved in order to obtain the current distribution throughout the model. Because finite element analysis is used to solve the model this could be very time consuming. Due to the computational complexity of the model it requires an advanced work station to solve the model, making it impractical for use on a typical personal computer. Secondly, MATLAB had to be used to calculate features such as the peak current position and centroid positions. For simplicity, all the elements of the current distribution model were implemented in MATLAB.

4.2.2 Current distribution model

The current distribution model predicted how current would spread from the stimulating electrodes, through the scala to the auditory nerve. Figure 4.1 gives an overview of the current distribution model that is discussed in this section. The flow diagram shows the different points at which the current distribution model outputs could be observed. Each of the model outputs at the different observation points gives a prediction of one of the different features. The term ‘features’ refers to the aspects of the resulting current spread pattern or neural activation pattern that may be used by the central auditory nervous system to extract pitch.

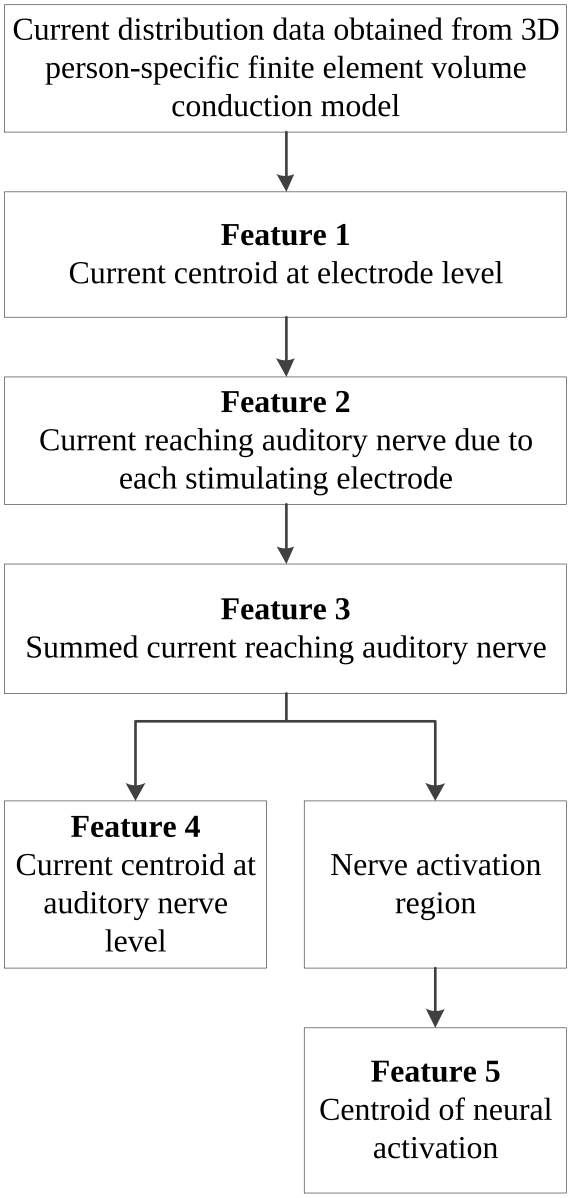


Figure 4.1. Summary of the different points at which the current distribution model outputs could be observed.

When current steering is carried out using simultaneous stimulation it is hypothesised that the currents from the two stimulating electrodes are summed to create a summed current distribution (McDermott and McKay, 1994). It is suggested that this resultant current distribution will result in a single place pitch rather than two pitches (one for each stimulating electrode). It is proposed that the place pitch is created by the centroid of the stimulation pattern. Some literature suggests that the place pitch corresponds to the centroid of the current levels applied to each electrode (Laneau *et al*., 2004). Other literature suggests that the place pitch is caused by the centroid of the summed current reaching the auditory nerves because of current distribution through the cochlea (Venter, 2015). Both these features, the centroid of a current distribution at electrode level (feature 1) and the centroid of the current reaching the nerve fibres (feature 4), were predicted using the person-specific current distribution model.

When current steering is carried out using sequential stimulation it is hypothesised that a place pitch is created by the centroid of the distribution of the neural activation (McDermott and McKay, 1994, Frijns *et al*., 2009). This is another feature (feature 5) that was predicted using the person-specific model described in this chapter.

The place pitch of a sound is determined by the place of stimulation in the cochlea (Kwon *et al*., 2011). As discussed in Chapter 2, when an electrode is stimulated, the stimulation current distributes through the cochlea and causes a certain extracellular voltage potential at the auditory nerve. The neural excitation at a certain position along the auditory nerve is dependent on the intracellular and extracellular voltage potentials of the neurons at the given position (Macherey and Carlyon, 2012). Neurons will only fire once a certain voltage potential threshold is reached. For this reason, it is assumed that there is a greater possibility that neural activation will take place (and that a place pitch will be created) at the position along the auditory nerve where maximum current can be measured. The position of maximum current along the auditory nerve because of electrical stimulation was another feature (feature 2 and feature 3) that was predicted using the person-specific current distribution model.

The main objective of the current distribution model was to compare model predictions of each of the different proposed features resulting from electrical stimulation, that may underlie place pitch perception, with measured pitch ranking results obtained through psychoacoustic experiments (Section 3.2). In summary, the different features included

1. the position of the centroid of the current levels applied to the stimulating electrodes (feature 1);

2. the cochlear position of the peak current at the auditory nerve because of the current decay from the two individual stimulating electrodes to the nerve fibre array (feature 2);
3. the cochlear position of the peak current at the auditory nerve because of the summed current of the two stimulating electrodes (feature 3);
4. the cochlear position of the centroid of the summed current distribution that reaches the auditory nerve (feature 4); and
5. the cochlear position of the centroid of the area of neural activation (feature 5).

Each person-specific current distribution model consisted of a rolled-out cochlea, including both the electrode array and the auditory nerve. The person-specific MATLAB models consisted of the same number of electrodes and nerve fibres as their corresponding 3D volume conduction models (Malherbe *et al*., 2015).

The resistance from each electrode to each nerve fibre was determined using the volume conduction models discussed in Section 4.2.1. The resistance was used in the MATLAB current distribution model to determine the current decay from each electrode to each nerve fibre. The current decay can be expressed as

$$Decay = 20\log\left(\frac{current\ at\ nerve\ [\mu A]}{current\ at\ electrode[\mu A]}\right)\ dB. \tag{4.1}$$

Section 3.2.1.3 describes how loudness balancing was done during the psychoacoustic experiments to ensure that the different stimuli were equal in loudness before the pitch ranking procedure commenced. The loudness balanced values of each of the stimuli of each of the psychoacoustic experiments in Section 3.2 were used as the inputs of the current distribution model. The loudness balanced values for each of the stimuli for each of the experiments of listener S25 are shown in Table 4.1 as an example of the inputs of the MATLAB current distribution model.

Table 4.1 The loudness balanced values for each of the stimuli for each of the current steering experiments of listener S25 as an example of the inputs of the MATLAB current distribution model. Each of the stimuli consisted of two stimulating electrodes. The currents applied to each electrode are given in the table in micro-Ampere.

Experiment	Stimulus A (Input current (µA))		Stimulus B (Input current (µA))		Stimulus C (Input current (µA))		Stimulus D (Input current (µA))	
	Electrode A	Electrode B	Electrode A	Electrode B	Electrode A	Electrode B	Electrode A	Electrode B
E1	17.5	709.38	531.36	684.22	684.22	512.51	722.31	17.5
E2	17.5	762.52	613.95	762.52	776.42	560.95	804.98	17.5
E3	17.5	735.47	541.05	722.31	722.31	560.95	722.31	17.5
E4	17.5	790.57	571.17	762.52	762.52	592.17	776.42	17.5
E5	17.5	709.38	541.05	709.38	709.38	541.05	709.38	17.5
E6	17.5	748.88	571.17	709.38	762.52	550.91	790.57	17.5
E7	17.5	964.31	696.69	930.1	930.1	722.31	947.05	17.5
E8	17.5	930.1	684.22	897.1	913.45	696.69	930.1	17.5
E9	17.5	913.45	659.95	881.05	897.1	696.69	897.1	17.5
E10	17.5	282.41	207.75	277.36	277.36	215.39	277.36	17.5
E11	17.5	272.39	211.54	267.52	287.56	211.54	282.41	17.5
E12	17.5	292.8	223.32	282.41	309.1	227.39	303.57	17.5
E13	17.5	231.53	186.42	235.75	244.42	179.81	240.05	17.5
E14	17.5	240.05	193.27	235.75	262.73	186.42	258.03	17.5
E15	17.5	248.87	204.04	253.41	267.52	193.27	262.73	17.5

The current distribution, from each stimulating electrode to each of the nerve fibres in the model, was calculated for each of the loudness balanced stimuli using the decay values that were calculated using (4.1). As shown in Table 3.3, each stimulus consisted of two stimulating electrodes. The resulting current distribution of a single stimulating electrode of each electrode pair, as well as the resulting current distribution of the simultaneous dual-electrode stimulus, was calculated.

Feature 2 and feature 3 in Figure 4.1 were predictions that could be observed at the output of the current distribution model. As shown in Figure 4.1, the first feature was the centroid of the current levels applied to the stimulating electrodes. This feature was realised through the implementation of the centroid model of place pitch, proposed by Laneau *et al*. (2004). It was stated that the centroid c, of the currents at electrode level, can be expressed by

$$c = \frac{\sum_e ea(e)}{\sum_e a(e)}, \tag{4.2}$$

where e is the electrode identifier and $a(e)$ is the average stimulation amplitude on electrode e (Laneau *et al*., 2004).

This centroid model only includes the stimulation amplitude of the stimulating electrodes. It does not account for factors such as current spread and the distance between the electrode array and the auditory nerve (Venter, 2015). Including such factors and calculating the current centroid at the auditory nerve level, rather than calculating the centroid at electrode level, may result in a feature that can more accurately be related to pitch ranking data of CI users.

To find a possible explanation for individual differences in pitch ranking data between CI users, the model in (4.2) was adapted to include the effect of current spread (Venter, 2015). In the model of Venter (2015) the electrode array was modelled to be 0.5 mm from the auditory nerve. Neurons were placed next to each other in the model to form the auditory nerve. When an electrode is stimulated, current spread occurs from the electrodes to the auditory nerve. Venter (2015) modelled the current spread by calculating the current that reached each of the ANs. The current was calculated as a function of the distance between the stimulating electrode and the AN, using a fixed current decay rate. The current from each stimulating electrode that reached each nerve fibre was summed at each nerve fibre in the model of Venter (2015). Once the total current at each nerve fibre had been calculated, the centroid of the currents reaching the AN level was calculated, using

$$c = \frac{\sum_k d(k)n(k)}{\sum_k n(k)}, \tag{4.3}$$

where $d(k)$ is the distance along the AN array from the base of the cochlea to the k^{th} nerve fibre and $n(k)$ is the total current reaching the k^{th} nerve fibre.

Venter (2015) made predictions about the current centroid position using different current decay rates; current decay rates of 1, 2, 3.6 and 5 dB/mm were used. The cited study related the model predictions, obtained using each of the different current decay rates, to measured pitch ranking data. It was found that using a current decay rate of 3.6 dB/mm in the model resulted in centroid predictions that had good correspondence with the average pitch ranking data of the listeners who participated in that study (Venter, 2015).

The model in (4.3) was implemented to realise the fourth feature. However, instead of using general values to determine $n(k)$, the person-specific current distribution model was used.

The fifth feature that was tested was the centroid of the neural activation region. Considering Figure 4.3, it is seen that the current amplitude of the current distribution creates a clear peak, whereafter the current amplitude seems to saturate towards the apex. The activation region was chosen as the region along the auditory nerves where the current amplitude was higher than the saturation amplitude. Neurons are activated when action potentials fire. This means that neurons only have two states, either activated or not activated. Because of this, assuming the current was enough to activate the neurons in a certain area, the centroid of the neural activation was found at the centre of the activation region.

4.2.3 Validity of the model

To ensure that the current distribution model gave accurate results, it was validated using the 3D, person-specific, finite element, volume conduction model. The loudness balanced stimuli (see Table 4.1) used in the current steering experiments were applied to the relevant electrodes of the volume conduction model and the MATLAB implementation of the current distribution model respectively. The current values were measured in both models at each of the nerve fibres. The current values at the nerve fibres of the two models were identical. The centroids and neural activation regions could be determined once it was known that the current decay had been implemented correctly in the current distribution model.

4.3 RESULTS

This section will present the model predictions for each of the features.

4.3.1 Model predictions

4.3.1.1 Feature 1

Feature 1 was the position along the electrode array of the centroid of the current levels applied to the stimulating electrodes. This centroid was calculated using (4.2). Figure 4.2 shows the predicted centroid positions along the electrode array for each of the person-specific models.

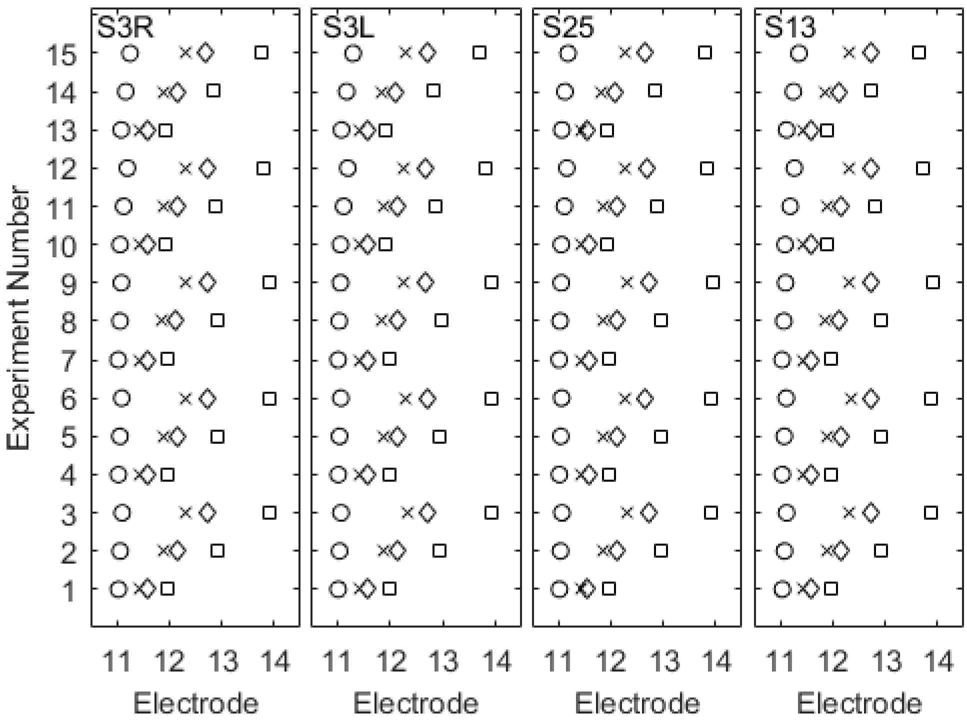


Figure 4.2 Model predictions of the position of feature 1 along the electrode array for each of the person-specific models. Stimuli A, B, C and D are represented by a square, diamond, cross and circle respectively.

The predicted perceptual distance between the stimuli increased, as the second stimulating electrode was further away from electrode 11 and closer towards the apex. The general pattern of the centroid positions remained the same between the different experiments. The predicted centroid positions of stimulus A and stimulus D (stimulus numbers referring to the naming convention in Chapter 3) were always located furthest away from each other. The centroid positions of stimulus B and stimulus C were always located in the middle between stimulus A and stimulus D. The predicted distance between stimulus C and stimulus D was always equal to the distance between stimulus A and stimulus B. The distance between stimulus B and stimulus C was considerably smaller than the distance between stimulus B or C and stimulus D. The distance between stimulus B and stimulus C was also considerably smaller than the distance between stimulus B or C and stimulus A. This meant that if this feature underlay place pitch perception, the listeners would probably be able to distinguish easily between stimulus A and any of the other stimuli and to distinguish easily between stimulus D and any of the other stimuli, but would possibly often confuse stimulus B and stimulus C with one another.

Slight differences were observed within a single person-specific model between the centroid position of experiments that used the same stimulating electrodes, for example experiment 2 and experiment 5. It is assumed that these differences occurred because of the different stimulation parameters that were used for the different experiments, and the effect of these stimulation parameters on the perception of the sounds during loudness balancing.

Slight differences were also observed in the same experiment of the different person-specific models. These differences probably occurred because of person-specific differences (such as the position of the electrode in the cochlea), and how these differences affect the way in which each CI user perceives sounds during loudness balancing.

4.3.1.2 Feature 2

An example of the model prediction of the current level along the nerve fibre as a result of the current decay from the two individual stimulating electrodes to the nerve fibre is shown in Figure 4.3 for each of the stimuli. Feature 2 was the cochlear position of the peak current at the auditory nerve because of the above-mentioned current decay from the two individual stimulating electrodes to the nerve fibre array. The vertical lines in Figure 4.3 indicate the model predictions of feature 2 for each of the stimuli of experiment 3 of the person-specific model of listener S3R.

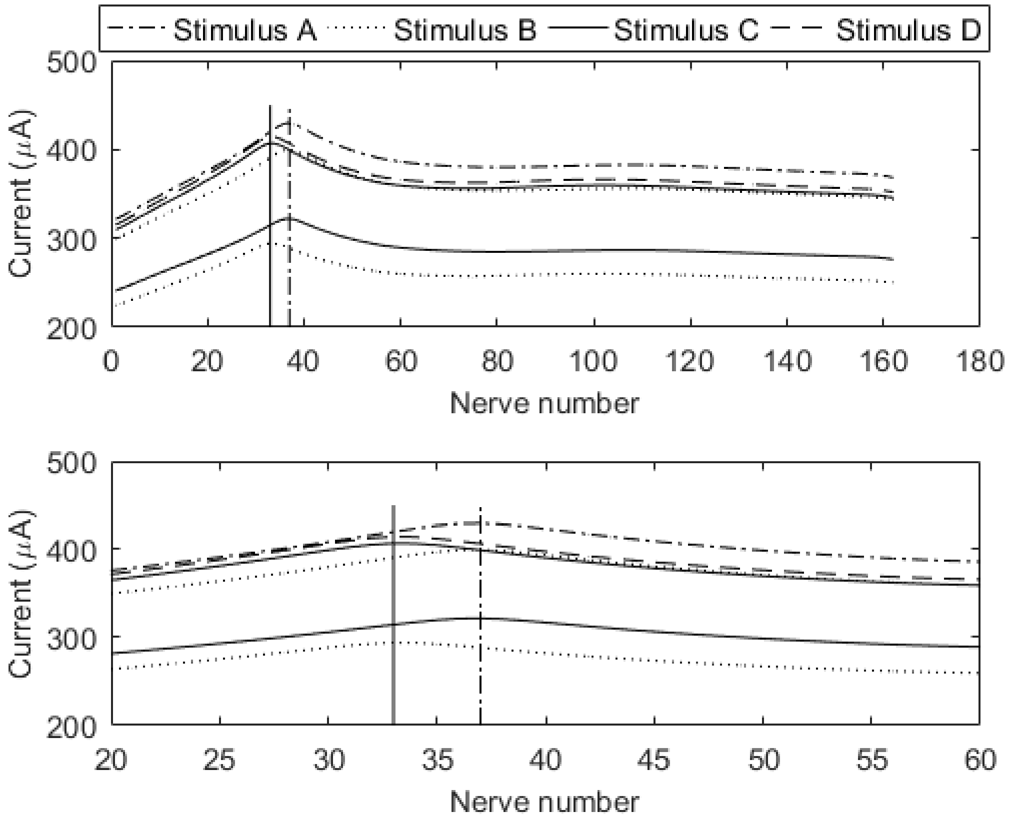


Figure 4.3 Current distribution at the auditory nerve as a result of the current decay from the two individual stimulating electrodes to the nerve fibre. The cochlear position of the peak current at the auditory nerve (feature 2) is indicated by the vertical lines. The vertical line of stimulus B is underneath the vertical line of stimulus A, because the peak current positions of these two stimuli are at the same place along the auditory nerve. Similarly, the vertical line of stimulus D is underneath the vertical line of stimulus C. The top panel shows all the nerve fibres of the model, while the lower panel only shows the nerve fibres surrounding the peak current position.

The predictions of feature 2 for each of the experiments and each of the person-specific models are shown in Figure 4.4 and Figure 4.5. Figure 4.4 shows the predictions of feature

2 in terms of nerve number as predicted by the person-specific model. The distance along the cochlea from the base to the predicted nerve number was calculated. This distance was substituted into (2.1) to find the frequency that can probably be associated with the position of each prediction of feature 2. These frequency predictions are shown in Figure 4.5.

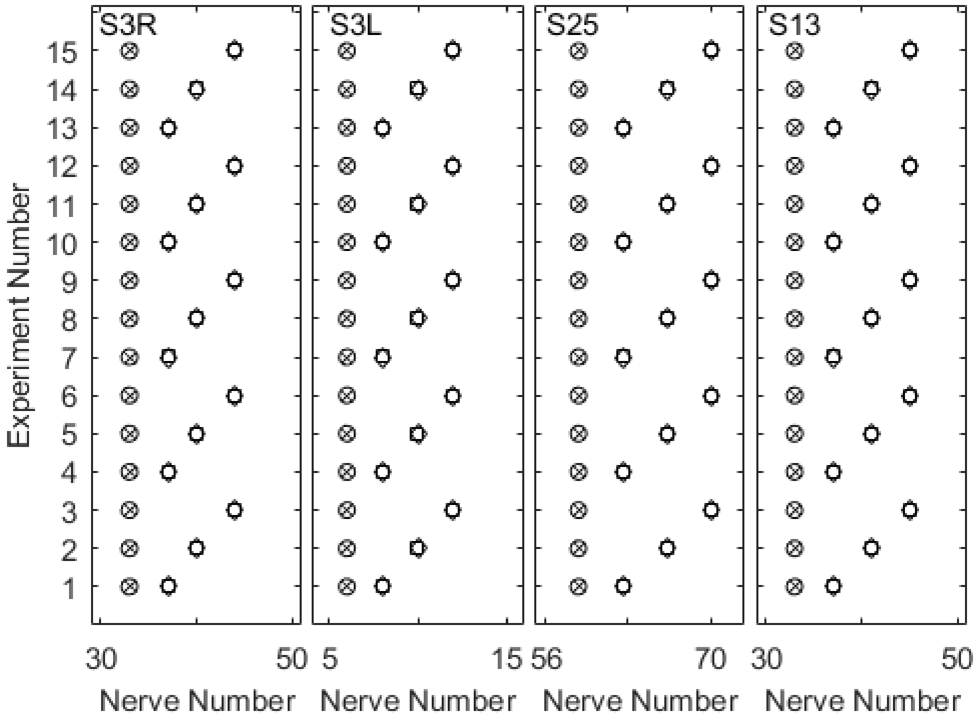


Figure 4.4 Model predictions of the position of feature 2 along the auditory nerve for each of the person-specific models. Stimuli A, B, C and D are represented by a square, diamond, cross and circle respectively.

Figure 4.4 and Figure 4.5 show that feature 2 is always located at one of two positions along the auditory nerve. The two positions always correspond with the position of the nerve fibre that is closest to the stimulating electrode of the two stimulating electrodes of any stimulus, with the highest amount of current applied to it. Therefore, feature 2 is located at the same position for stimuli A and B and feature 2 is located at the same position for stimuli C and D. Because of this, it was expected that a listener who relies on feature 2 to determine place pitch would probably find it difficult to distinguish between stimuli A and B, difficult to distinguish between stimuli C and D, and easy to distinguish between stimuli A or B and stimuli C or D. Reconsidering the MDS results in Section 3.2.2 shows that listener S25 may possibly have relied on feature 2 to estimate place pitch.

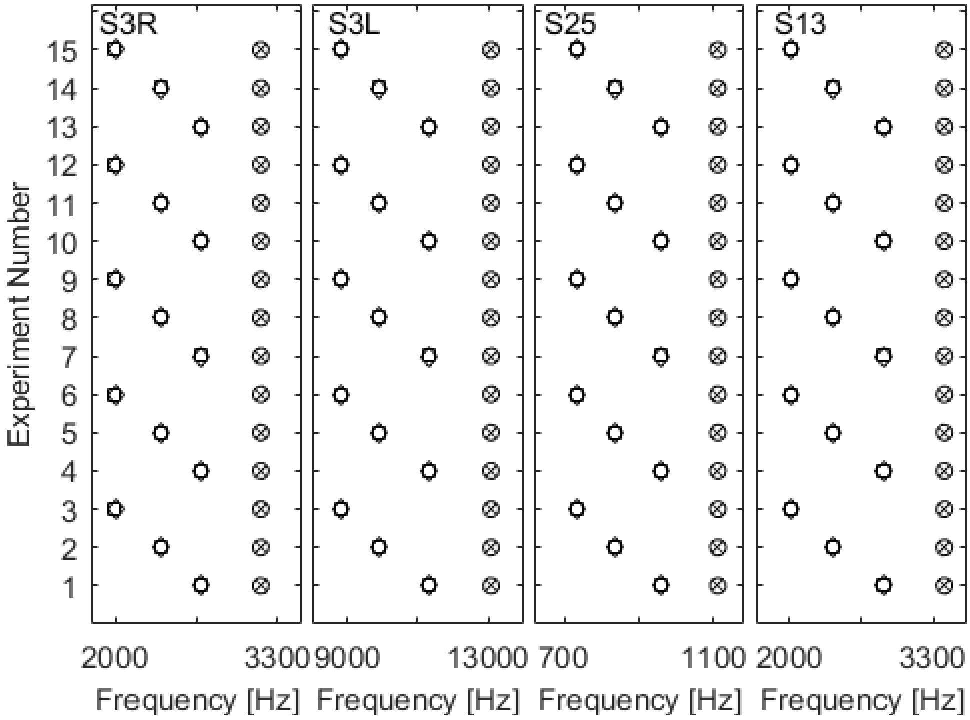


Figure 4.5 Frequency representation of the predictions of the position of feature 2 along the auditory nerve for each of the person-specific models. Stimuli A, B, C and D are represented by a square, diamond, cross and circle respectively.

The figures also showed that similar to feature 1, feature 2 is influenced by the electrode distance between stimulating electrodes. As the second stimulating electrode moves further away from electrode 11 and closer towards the apex, feature 2 also moves closer to the apex. Contrary to the observations of feature 1, there are no differences between the predicted position along the auditory nerve for different experiments that used the same electrode distance (for example experiments 2 and 5). This could mean that the resolution of the model is not small enough to indicate the effect of small changes in the amount of current applied to each stimulating electrode (see Table 4.1) at the auditory nerve level. Adding more nerve fibres could potentially improve the model resolution. This finer resolution was unnecessary for the purpose of the present study because even if, for example, the results of experiments

2 and 5 were slightly different from each other, feature 2 of stimuli A and B and feature 2 of stimuli C and D of a specific experiment would still be located in the same position.

In the model, nerve fibre number 1 is located at the base of the cochlea. For listener S3L, feature 2 is located at nerve number 6 for stimuli C and D. For listener S3R, feature 2 is located at nerve number 33 for stimuli C and D. As mentioned, Figure 4.4 shows that feature 2 corresponds to the position of the nerve fibre that is closest to the stimulating electrode with the highest amount of current applied to it. The difference between the position of stimuli C and D of listener S3R and S3L is an indication that the electrode insertion depth of listener S3R is considerably deeper than that of listener S3L. This is confirmed by considering the 3D volume conduction models of these listeners (Malherbe *et al*., 2015).

Note that the pattern of the position and order of the stimuli does not change, irrespective of whether feature 2 is represented in terms of nerve number or frequency. Frequency is simply a mathematical conversion of the nerve number. If the frequency positions were normalised and the nerve number positions were normalised, both would be in the same position. The frequency representation provides better understanding and a more general representation of the position of each nerve fibre in the cochlear model.

4.3.1.3 Feature 3

Figure 4.6 shows an example of the model predictions of the current level along the nerve fibre as a result of the summed current of the two stimulating electrodes. Feature 3 was the cochlear position of the peak current at the auditory nerve because of the summed current of the two stimulating electrodes. The model predictions of feature 3 for each of the stimuli of experiment 3 of the person-specific model of listener S3R is indicated by the vertical lines in Figure 4.6.

The predictions of feature 3 for each of the experiments and each of the person-specific models are shown in Figure 4.7 and Figure 4.8. Figure 4.7 and Figure 4.8 show the predictions of feature 3 in terms of nerve number and frequency respectively.

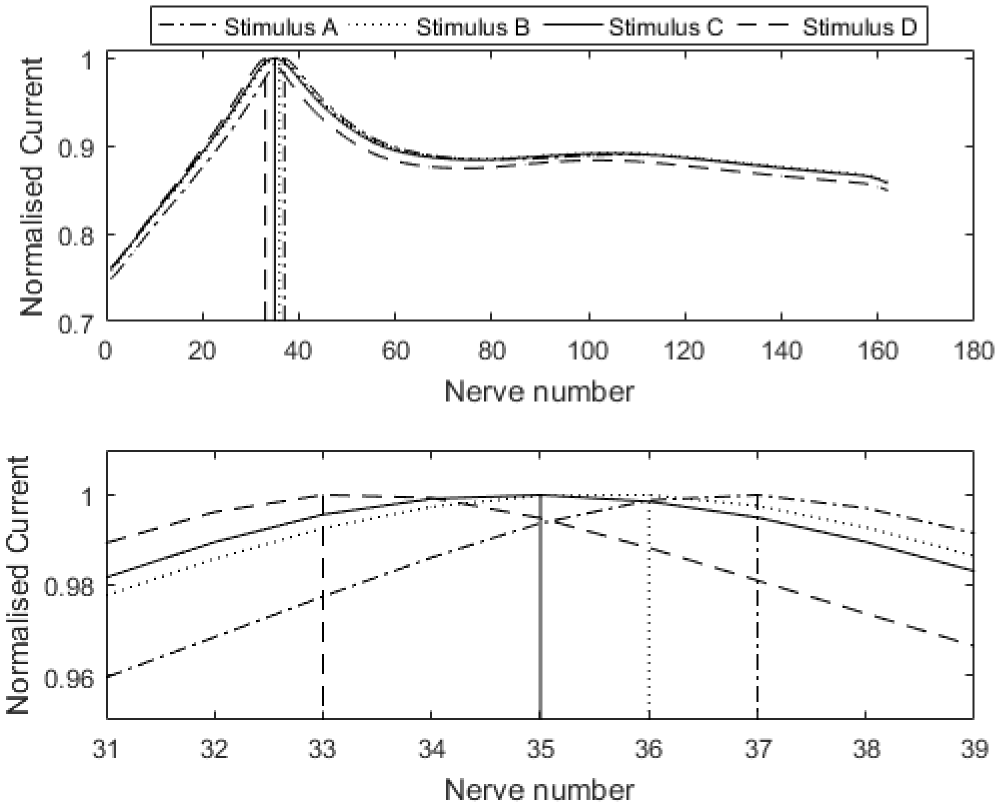


Figure 4.6 Normalised current distribution at the auditory nerve as a result of the summed current of the two stimulating electrodes. The cochlear position of the peak current at the auditory nerve (feature 3) is indicated by the vertical lines. The top panel shows all the nerve fibres of the model, while the lower panel only shows the nerve fibres surrounding the peak current position.

The predictions of feature 3 of listener S3R are similar to those of feature 2, with smaller distances between stimuli A and B and between stimuli C and D, and greater distances between stimuli A or B and stimuli C or D for most experiments. However, for experiments with electrode separation distances of one electrode (for example experiment 1), stimuli B and C were located in the same position with a small distance between these two stimuli and stimulus A or stimulus D.

The predictions of feature 3 of listener S25 were much more similar to the prediction of feature 1, with smaller distances between stimuli B and C, and greater distances between these two stimuli and stimuli A or D. The predictions of feature 3 of listener S13 were very similar to those of listener S25, except for the experiments with electrode separation distances of one electrode, which were the same as those of listener S3R. Feature 3 of stimuli

B, C and D of listener S3L were cluttered while stimulus A was located at a greater distance from them.

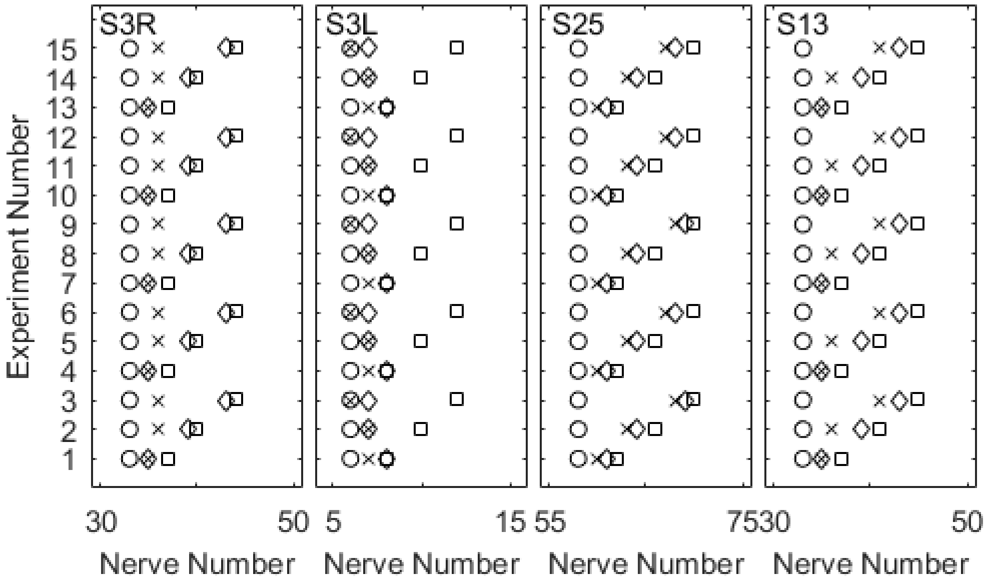


Figure 4.7 Model predictions of the position of feature 3 along the auditory nerve for each of the person-specific models. Stimuli A, B, C and D are represented by a square, diamond, cross and circle respectively.

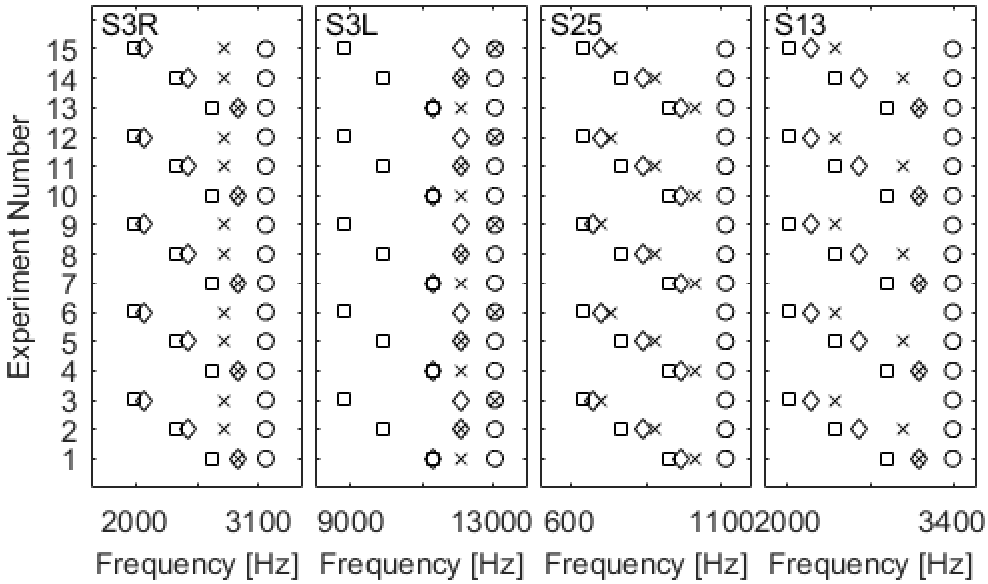


Figure 4.8 Frequency representation of the model predictions of the position of feature 3 along the auditory nerve for each of the person-specific models. Stimuli A, B, C and D are represented by a square, diamond, cross and circle respectively.

Feature 3 is the first feature that produces considerably different predictions between the different person-specific models. The differences might be insightful when the predictions are compared to measured results, since the measured pitch ranking results of each listener were considerably different.

4.3.1.4 Feature 4

Figure 4.9 shows an example of the model predictions of the current level along the nerve fibre as a result of the summed current of the two stimulating electrodes. Feature 4 was the cochlear position of the centroid of the summed current distribution reaching the auditory nerve. This feature was predicted using (4.3). The vertical lines in Figure 4.9 show the model predictions of feature 4 for each of the stimuli of experiment 3 of the person-specific model of listener S3R.

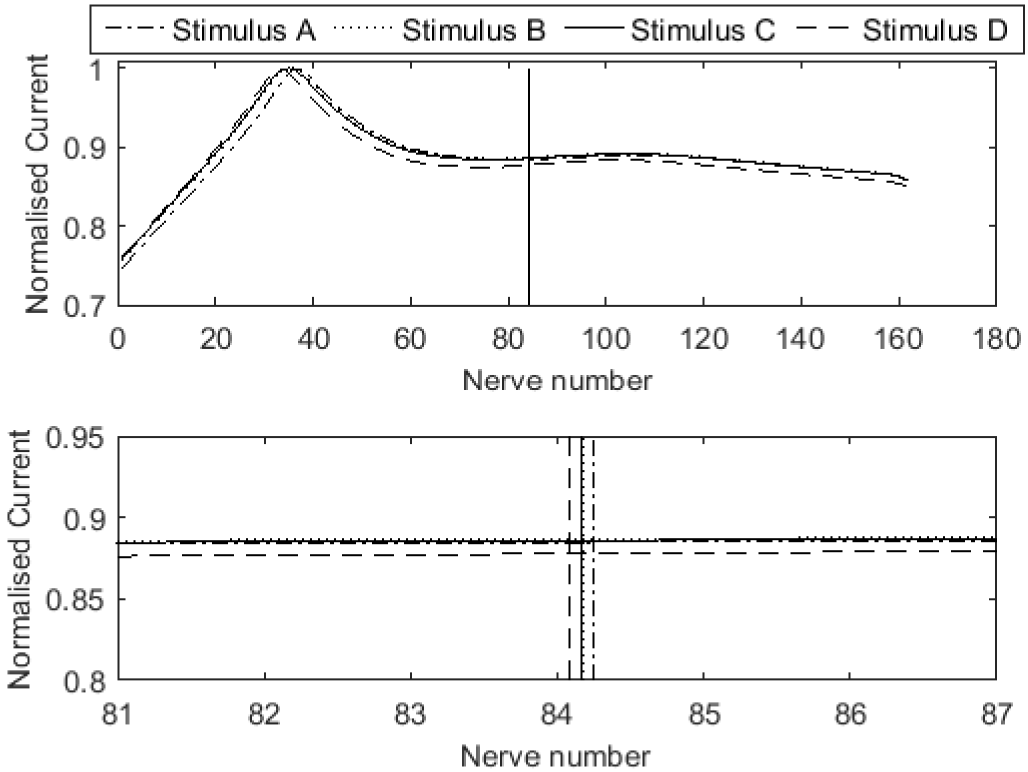


Figure 4.9 Normalised current distribution at the auditory nerve as a result of the summed current of the two stimulating electrodes. The cochlear position of the centroid of the summed current distribution that reaches the auditory nerve is indicated by the vertical lines. The top panel shows all the nerve fibres of the model, while the lower panel only shows the nerve fibres surrounding the centroid position.

Figure 4.10 and Figure 4.11 show the predictions of feature 4 in terms of nerve number and frequency, for each of the experiments and each of the person-specific models. The prediction pattern of feature 4 looks similar to the predictions of feature 1. This is not surprising, since both features were based on similar mathematics. Feature 1 was a centroid prediction at electrode level, while feature 4 considered current distribution through the cochlea from the stimulating electrodes to the auditory nerve and gave a centroid prediction at the auditory nerve level. In Figure 4.10 and Figure 4.11 it was interesting to note that the model predicts that the positions of the centroid of the current distribution at neural level of the different stimuli would be very close to one another. In most instances, the predicted positions of the centroids of the stimuli were less than one nerve fibre distance apart.

Also note how the predicted positions of feature 4 were all between nerve fibres 83 and 86, while the electrodes were stimulating closer to the area of nerve fibres 33 to 45 of listeners S3R and S13, 6 to 12 of listener S3L and 58 to 70 of listener S25. The positions of the centroids are mathematically correct and the predictions of feature 4 seem logical when the current distribution in Figure 4.9 is considered. The distribution shows that there is very little current in the base of the cochlea; a current peak is formed at the neurons close to the stimulating electrodes, whereafter the current distribution stabilises at a value lower than the peak, but higher than the current values in the base, as it spreads through the rest of the cochlea towards the apex. The long “tail” that forms after the current peak pulls the centroid more towards the apex of the cochlea.

Although this is mathematically correct, it does not seem sensible in practice that this feature can underlie place pitch. A certain amount of current is needed to evoke action potentials to activate the nerve fibres. No neural activation can take place at the predicted positions of the centroids because the current level at these positions is too low to evoke action potentials. This discussion is continued in Section 4.3.2.2.

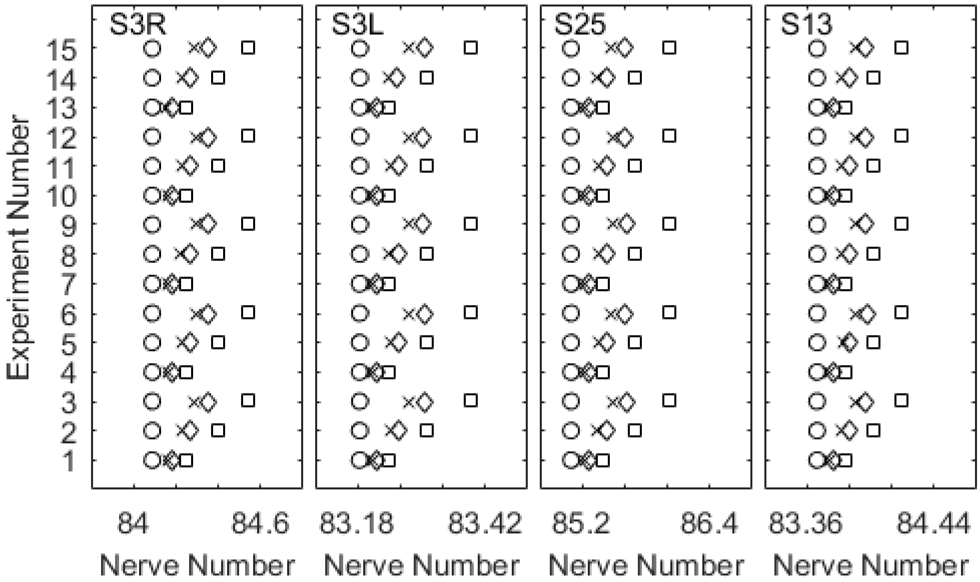


Figure 4.10 Model predictions of the position of feature 4 along the auditory nerve for each of the person-specific models. Stimuli A, B, C and D are represented by a square, diamond, cross and circle respectively.

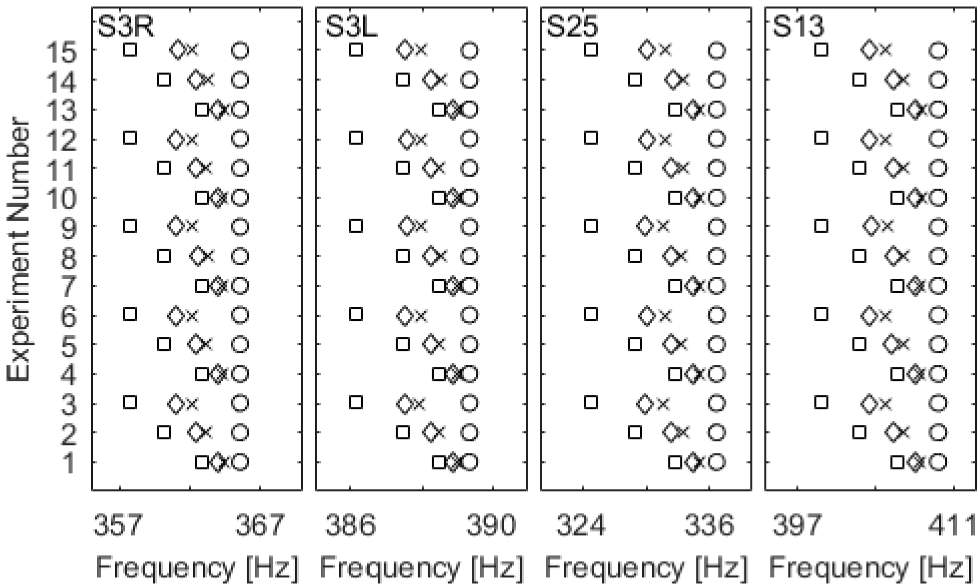


Figure 4.11 Frequency representation of the model predictions of the position of feature 4 along the auditory nerve for each of the person-specific models. Stimuli A, B, C and D are represented by a square, diamond, cross and circle respectively.

4.3.1.5 Feature 5

Feature 5 was the cochlear position of the centroid of the area of neural activation. Figure 4.12 shows an example of the model predictions of the current level along the nerve fibre as a result of the summed current of the two stimulating electrodes. The assumption was that nerve fibres would activate when the current reaching the nerve fibre was higher than the horizontal lines in the figure. The centroid of the area of neural activation was found at the centre of the area of neural activation.

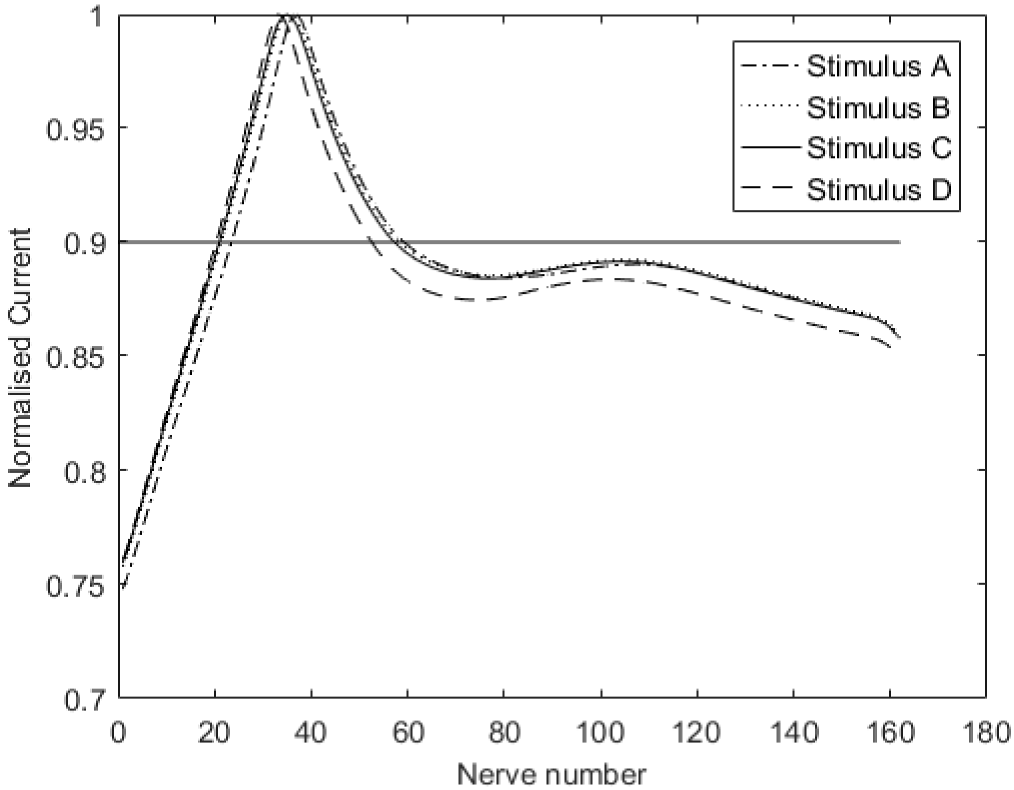


Figure 4.12 Normalised current distribution at the auditory nerve as a result of the summed current of the two stimulating electrodes. The cochlear position of the centroid of the area of neural activation is found at the centre of the neural activation area. It was assumed that neural activation will take place when the current is higher than the horizontal line.

Figure 4.13 and Figure 4.14 show the predictions of feature 5 in terms of nerve number and frequency, for each of the experiments and each of the person-specific models.

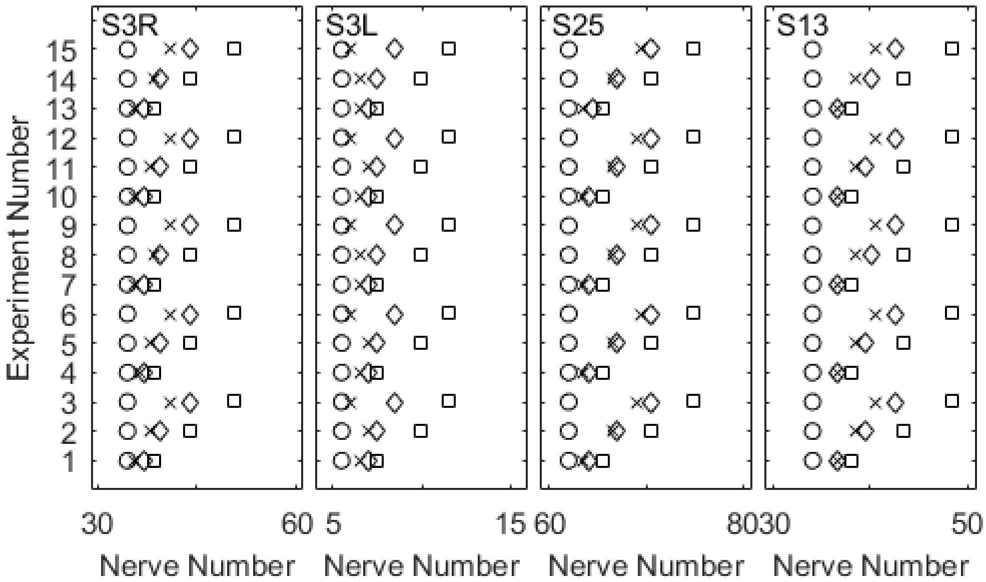


Figure 4.13 Model predictions of the position of feature 5 along the auditory nerve for each of the person-specific models. Stimuli A, B, C and D are represented by a square, diamond, cross and circle respectively.

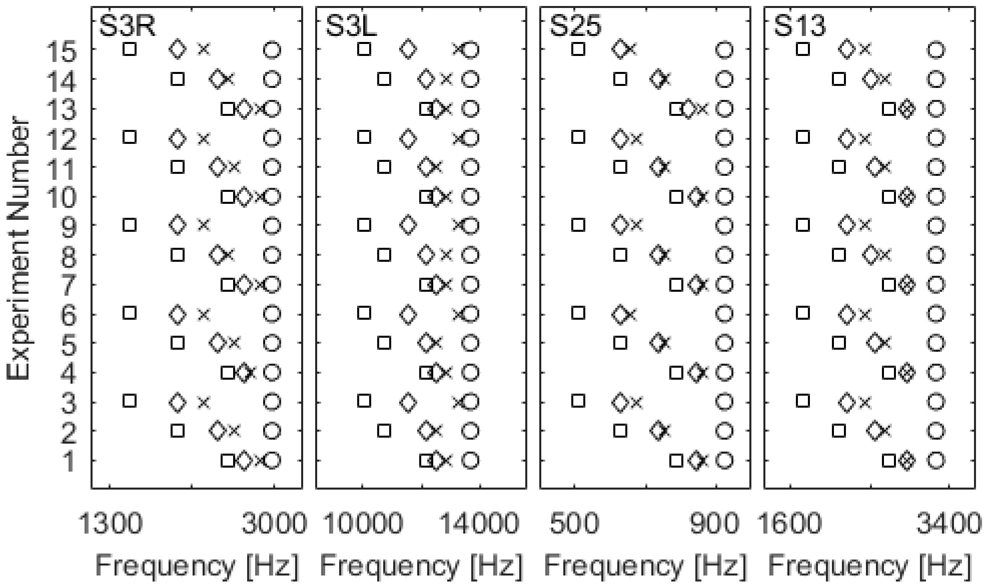


Figure 4.14 Frequency representation of the model predictions of the position of feature 5 along the auditory nerve for each of the person-specific models. Stimuli A, B, C and D are represented by a square, diamond, cross and circle respectively.

The prediction pattern of feature 5 of the models of listeners S3R, S25 and S13 are very similar to that of feature 1. There is a small distance between the predicted positions of stimuli B and C, a larger distance between stimuli B or C and stimulus A, and a larger distance between stimuli B or C and stimulus D. The predictions of feature 5 for listener S3L were slightly different from those of feature 1 for this listener. The predictions of feature 5 showed that, especially for experiments where electrode separation distances of three electrodes were used (for example experiment 3), the positions of stimuli C and D were close to each other, while there were greater distances between these two stimuli and stimuli A and B. Stimulus B was predicted to be more or less at the centre between stimulus A and stimuli C or D when an electrode separation distance of three electrodes was used. The predicted pattern of feature 5 of the stimuli of listener S3L seemed to be more similar to that of the models of the other listeners at smaller electrode separation distances. If this feature underlay place pitch, the measured results of most of S3R, S25 and S13 would be similar, while those of S3L would differ at electrode separation distances of three electrodes.

4.3.2 Relating model predictions of different features to measured data

The utilisation of the above-mentioned features in the pitch ranking experiments (discussed in Section 3.2) were analysed by relating the predicted feature values to the perceived pitch positions of the four stimuli that were presented for each experiment in Figure 3.5. Compared to the nerve number, the frequency representation of the predicted features provides a representation that is easier to understand, analyse and compare with other literature. For this reason, the frequency representation of the predicted features was used in the analyses that follow. Two methods were used to analyse the feature utilisation in the pitch ranking experiments: correlation and mutual information (MI) (Oosthuizen, 2017).

4.3.2.1 Correlation results

The predicted results of each feature for each of the four listeners, S3R, S3L, S25 and S13, were correlated with the MDS results of these listeners that were shown in Figure 3.5 to analyse the feature utilisation during the pitch ranking experiments. Figure 4.15 shows the correlation results. A large correlation coefficient suggests that the feature is being used, while a small coefficient indicates that the feature is not used (Oosthuizen, 2017).

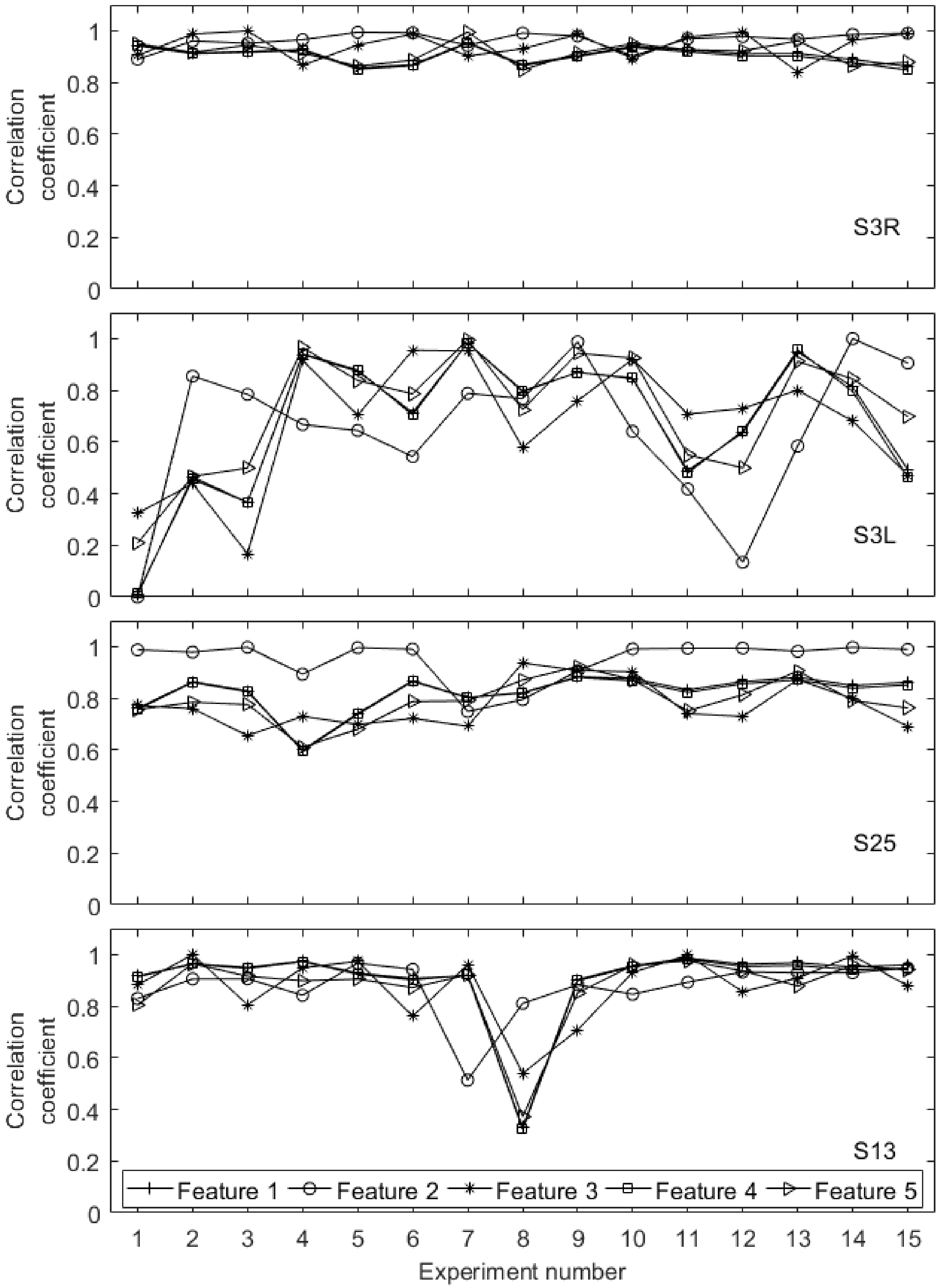


Figure 4.15 Correlation between the predicted features and the measured results.

The correlation results in Figure 4.15 were fairly consistent with the results shown in Figure 3.12 in the sense that the experimental data often correlated highly with the model predictions in the experiments where the listeners achieved a high percentage of correct results. The listeners also performed worse in the experiments where there was low correlation between the model predictions and the measured data. Perhaps the place pitch features were not available to the listeners under the specific stimulation parameters of these experiments where they performed poorly. It could be possible that the place pitch features were masked by another factor, for example, as discussed in Section 3.2.4.2, the familiarity of the stimulation rate.

For most experiments of each listener, there was no clear difference (not statistically tested) between the correlation results of the different features. However, for most of the experiments of listener S25, the correlation coefficients of feature 2 were slightly higher than the correlation coefficients of the other features. The prominent utilisation of feature 2 by listener S25 was according to expectation, as stated in Section 4.3.1.2.

For three out of the four listeners, S3R, S25 and S13, most of the features correlated highly with the measured data, which could suggest that all the features were used by the listeners. This may suggest that all the features described in literature are the same feature expressed in different ways. The position of the peak current and the centroid of the current distribution would lead to a specific neural activation pattern, which would determine the pitch that is perceived by the listener. If all the features are related to place pitch, since all the features correlated highly with the measured data, this observation suggests that current steering carried out using sequential stimulation does control the place pitch mechanism. The high correlation results suggested that place pitch was steered and changed as current steering was applied.

The fact that all the features correlated highly with the measured data could also mean that correlation alone does not give a complete evaluation of the relation between the different features and the measured data. When correlation results are considered in isolation, they could produce misleading results (Oosthuizen, 2017). Using correlation for the feature utilisation analysis is a good approach in the sense that it can accurately compare the order of the values of the pitch ranking results to the predicted features (Oosthuizen, 2017). However, correlation does not consider feature precision or the information present in the stimulus subsets (Oosthuizen, 2017). The information present because of the different stimulation parameters in the different experiments would more accurately be analysed by carrying out MI analysis. Using MI analysis could also be beneficial to see the effect that feature precision, which depends on the variance in the feature, has on feature utilisation. Oosthuizen (2017) stated that MI and correlation analysis could produce misleading results if considered in isolation, but the consideration of both approaches together may provide complementary perspectives on the data.

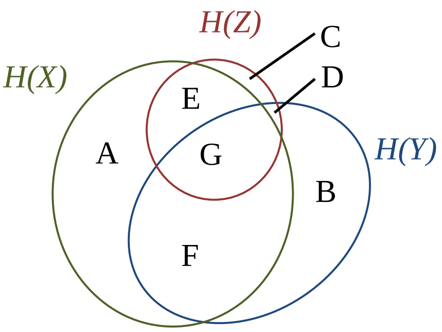
4.3.2.2 MI results

Based on Shannon's information theory (Shannon, 1948), Miller and Nicely (1955) developed the feature information transmission analysis (FITA) technique (Miller and Nicely, 1955). The FITA technique provides a way of quantifying the amount of information conveyed by a single feature in a psychoacoustic listening experiment (Oosthuizen, 2017). This technique is subject to some restrictions, which would prevent its use in the present study.

One restriction is that features have to be categorical and not continuous. Categorical features describe stimuli (for example the model predictions of the feature positions) using category labels, such as high, medium or low. Continuous features describe these stimuli by numeric values, for example in the present study the predicted feature positions could take on any frequency value within the range of 0 Hz to 20 kHz (Greenwood, 1990).

Another restriction is that the technique can typically only be used to analyse data from identification experiments and not to analyse data of other types of psychoacoustic experiments, such as the ranking experiments done in the present study, discrimination, detection and estimation experiments (Oosthuizen, 2017). Alternative techniques were developed to overcome these restrictions (Oosthuizen, 2017). The present study used one of these alternative techniques for the MI analysis. Oosthuizen (2017) labelled the MI technique used in this section the trial-based ranking FITA (R-FITA). The Venn diagram of Oosthuizen (2017), shown in Figure 4.16, can be used to summarise the trial-based R-FITA briefly.

In Figure 4.16 variables X, Y and Z represent stimulus, response and feature respectively. In the pitch ranking experiments of Section 3.2, variable X was a categorical variable representing the combination of the two stimuli presented in a trial during these experiments. Because the current steering experiments were designed to allow presentation of the same stimulus in both intervals of a trial, X had N^2 categories. Note that two stimulus pairs containing the same two stimuli, presented in a different order (for example (A, D) and (D, A)) were assigned to two different categories in X. Y was a categorical variable with two categories representing the interval selected by the listener. During the pitch ranking experiments of Section 3.2, the interval that had to be selected by the listener was labelled as higher-pitched. The feature variable Z was continuous.



$H(X)$	= A+E+F+G	$I(X,Y)$	= F+G
$H(Y)$	= B+D+F+G	$I(X,Z)$	= E+G
$H(Z)$	= C+D+E+G	$I(Y,Z)$	= D+G
$H(X\|Y)$	= A+E	$I(X,Y\|Z)$	= F
$H(Y\|X)$	= B+D	$I(X,Z\|Y)$	= E
$H(X\|Z)$	= A+F	$I(Y,Z\|X)$	= D
$H(Z\|X)$	= C+D	$I(X,Y,Z)$	= G
$H(Y\|Z)$	= B+F		
$H(Z\|Y)$	= C+E	H_f	= E+G
		T_{abs}	= G
		T_{rel}	= G/(E+G)

Figure 4.16 Venn diagram presented in Figure 4.7 of Oosthuizen (2017) (reproduced with permission of the author) of the entropies of random variables used in the calculation of another MI technique, the continuous FITA (C-FITA). From the explanation in Oosthuizen (2017), the area of each ellipse is proportional to the entropy of the represented variable (X, Y or Z) and the area of each overlapping region is proportional to the MI between the variables represented by the overlapping ellipses. Exactly the same Venn diagram is applicable to the R-FITA that was used in the present study.

The multivariate mutual information describes the information common to the stimulus, response and feature, T_{abs}=*I(X,Y,Z)* in Figure 4.16. The collective transmitted information is defined as T_{col}=*I(X,Y)*. T_{abs}, T_{col} and T_{abs}/T_{col} were studied to draw conclusions about the utilisation of the features discussed in the previous section during current steering experiments. For more detail on the trial-based R-FITA and how T_{col} and T_{abs} were calculated, see Oosthuizen (2017).

Other important notes on the MI analysis carried out in this section are as follows.

- *I(X,Y,Z)* will report maximum values if the listener responds correctly (according to expectation) to each stimulus. The maximum value of *I(X,Y,Z)* for the trail-based R-FITA is 1 (Oosthuizen, 2017).
- *I(X,Y,Z)* will report zero information transmission if the listener's responses are completely random and performance is at chance level.
- T_{abs} is sensitive to feature precision, which is presented by the standard deviation of the probability density function of the feature (Oosthuizen, 2017). When MI analysis is performed, a standard deviation value is chosen based on the uncertainty in the data. It has been shown that the standard deviation may also be replaced with an estimated just-noticeable difference (jnd) of the feature (Oosthuizen, 2017). Larger jnd values would be associated with lower precision.

It has been shown that the jnd varies vastly across listeners (Kwon and van den Honert, 2006). Since jnd was not measured for the specific listeners who participated in this study, a general assumption had to be made about the jnd of the features to complete the calculations for the MI analysis. It was assumed that the jnd of feature 1 was 0.25 electrode distances. For a jnd of 0.25 electrode distances the assumption was that the listener would be able to hear four discriminable pitches, as current was delivered to two specific electrodes. This seemed to be a fair assumption, since a study reported that data from 115 ears indicated that the number of discriminable pitches between two electrodes averaged 3.8, 6.0 and 5.3 for stimulation in the basal, mid and apical regions of the cochlea (Firszt *et al*., 2007).

Another study has shown that just-noticeable difference in frequency (jndf) for cochlear implant users in free field is between 0.2 and 3 speech processor filter widths (this varied across people and varied across place of stimulation) (Pretorius, 2011). Filter widths were 160 Hz in the areas where the jndf was measured. This means that the jndf was between 32 Hz and 480 Hz. These jndfs were assumed to be the jnd of features 2, 3, 4 and 5. T_{abs} were calculated at both these extremes. The results of the MI analysis follow.

The information metrics for the different experiments of the different listeners (for an assumed jndf of 32 Hz) are shown in Figure 4.17 and Figure 4.18. Figure 4.17 clearly shows the dominant effect of the electrode separation distance parameter (Table 3.2) on transmitted information in listeners S3R, S25 and S13. Experiments 3, 6, 9, 12 and 15, where the electrode separation distance was highest, show the largest T_{abs} and T_{col} values. Figure 4.17 also shows that almost no information was transmitted to listener S3L. This is consistent with the poor performance that was observed for this listener in Figure 3.12. Some information was transmitted to this listener during experiment 9. This listener also performed best during pitch ranking experiment 9, as indicated in Figure 3.12. The data trends observed in Figure 4.17 were consistent with those of the results shown in Figure 3.12. This suggests that, as expected, a listener's pitch ranking performance is directly relatable to the amount of information (captured in the spatial patterns represented in features 1 to 5) received by the listener.

Figure 4.17 shows almost no MI between feature 4 and the experimental data. This observation resonates with the observations made in Section 4.3.1.4. Section 4.3.1.4 showed how the feature predictions of the different stimuli of feature 4 were very close to each other. The distance between the positions of feature 4 of some stimuli was even smaller than 1 Hz. This means that this feature can only carry information if the jnd of this feature is very small (at least smaller than 1 Hz). A jnd frequency smaller than 1 Hz is unrealistic for CI users; NH listeners have jnds of 1 Hz up to about 500 Hz and these increase monotonically above this turning point (Sek and Moore, 1995). The low MI between feature 4 and the experimental data suggests that the current centroid at the auditory nerve level probably does not underlie place pitch.

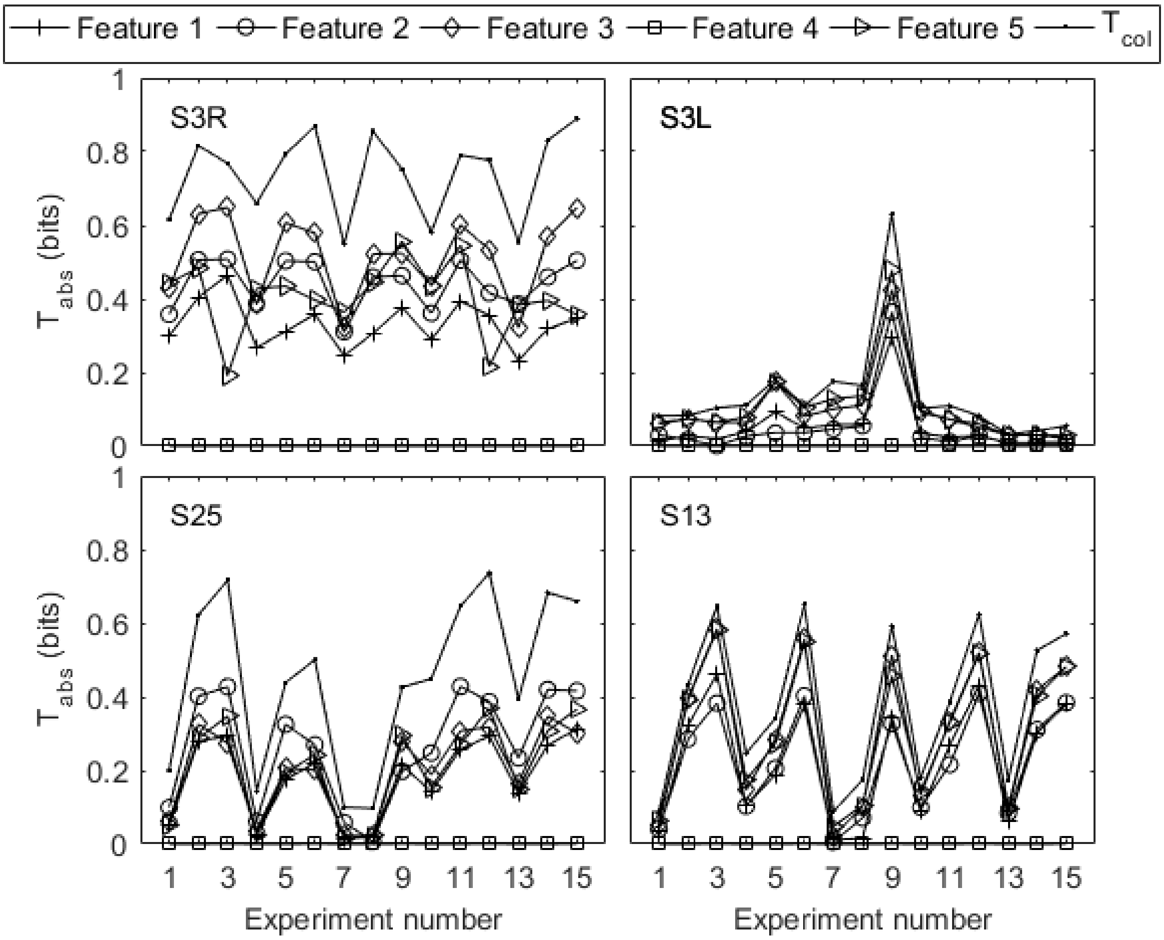


Figure 4.17 Information metrics for the different experiments of the different listeners with jndf = 32 Hz.

Similar to the correlation results, the information metrics in Figure 4.17 show that, apart from feature 4, there was no marked (although not statistically tested) difference between the MI result of the different features. Consistent with the correlation results, this suggests that the place pitch of the listener is probably influenced by all four these features because these four features are just different versions of the same underlying representation of place pitch. Because the shape of the cochlea of a single ear does not change over a short period (for example the time during which all the different experiments were completed), the current distribution throughout the cochlea of a specific ear from a specific electrode will always be more or less the same. This means that as the centroid moves between the stimulating electrodes, the peak of the distributed current will move. As the peak of the distributed current moves, the area of neural activation and neural centroid will move. The correlation between the features explains why the MI results show very similar results for these four features.

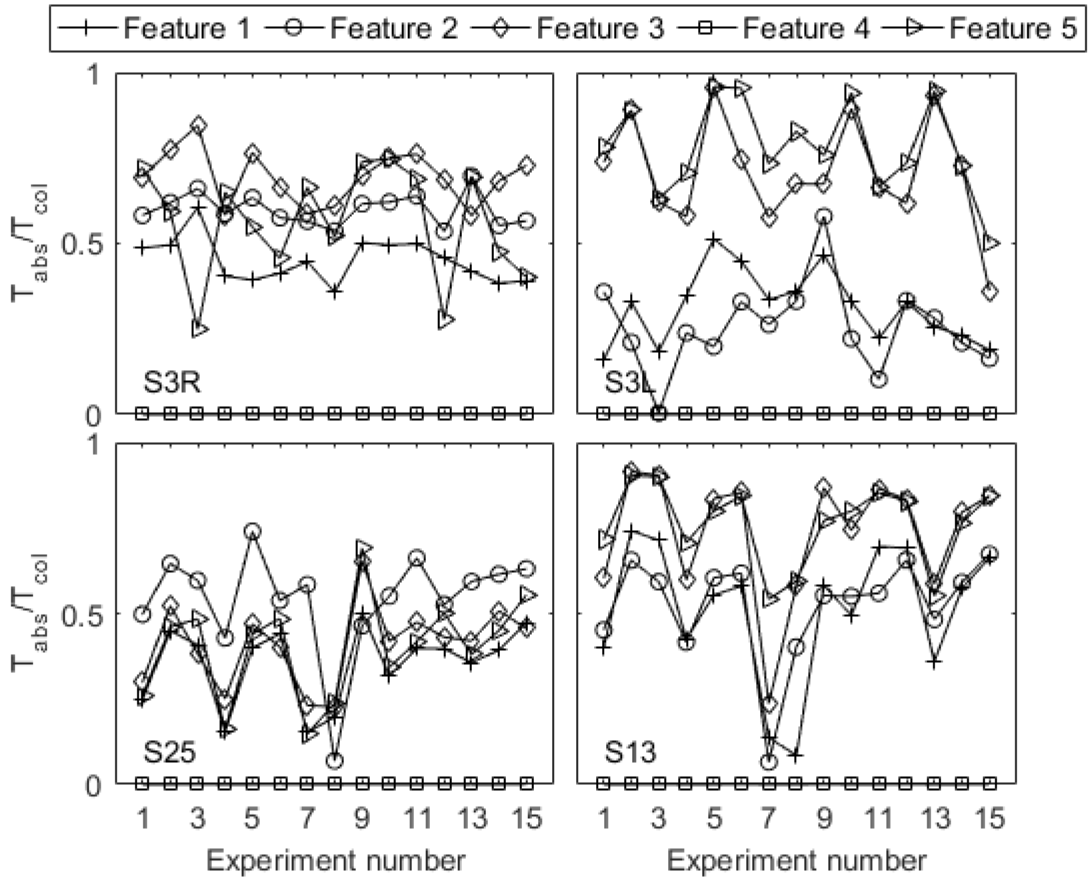


Figure 4.18 Normalised information metrics for the different experiments of the different listeners with jndf = 32 Hz.

Figure 4.18 shows the information common to the stimulus, response and feature normalised by the collective transmitted information. T_{abs}/T_{col}=1 for a specific feature if this feature contained all the information used by the listener. This means that none of the features contained all the information used by the listeners. Again, this could indicate that the listeners used a combination of features. However, it may also indicate that there may be other features that underlie place pitch, which have not been considered in the present study. Another interesting observation was that although little information was available to listener S3L, this listener used a large amount of the available information. As already observed in Figure 4.17, feature 4 contained little information used by this listener. Features 3 and 5 contained most of the information used by this listener and features 1 and 2 contained some information used by this listener.

Features 3 and 5 contained more information than the other features of the information used by listener S13. Feature 2 contained slightly more information than the other features of the information used by listener S25. No feature specifically contained more information than the others for listener S3R. These four features might be different representations of a single feature that underlie place pitch, but because of model inaccuracies it seems as if some listeners rely more on the information provided by certain features while other listeners prefer to use other features.

The information metrics for the different experiments of the different listeners (for an assumed jndf of 480 Hz) are shown in Figure 4.19 and Figure 4.20. These figures show that features 2 to 5 contained very little to almost none of the information used by the listeners. The result of feature 1 remained the same as the results observed in Figure 4.17 and Figure 4.18, because the jnd of this feature remained unchanged.

Considering the results in Figure 4.19 and Figure 4.20, the question arises why the MI between the features and the measured results was so low if these listeners were able to do the pitch ranking tasks. As suggested before, one answer could be that there are other features that underlie place pitch that were not considered. A more likely answer may be that 480 Hz is not the optimal choice for the jnd values used to calculate T_{abs}. Because the jnd values of features 2 to 5 were chosen as such a large value, the precision of these features was unrealistically small.

It is clear that the choice of jnd plays an important role in the calculation of the MI results. Choosing the incorrect jnd could result in misleading results. Even though the jndf measurements of Pretorius (2011) were made in free field, using jndf=32 Hz in the MI analysis of the present study complements the correlation results, the predictions in Section 4.3.1 and the experimental results in Figure 3.12. Listeners S3R and S13 of the present study also participated in the study conducted by Pretorius (2011). It was interesting to see that on average the jndf of these two listeners, which were measured by Pretorius (2011), were very close to 0.2 speech processor filter widths (or 32 Hz). This supports the observation of the present study that the jndf of these two listeners were closer to the bottom part of the jndf range (32 Hz – 480 Hz) of CI listeners compared to the upper part of the range. Although 32 Hz also seemed to be the optimal choice for the jndf of the other two listeners, S3L and S25, who participated in the present study, this does not mean that it can be assumed that a jndf of 32 Hz can always be used for the type of MI analysis conducted in the present study. As shown by Pretorius (2011), some listeners do have larger jndfs.

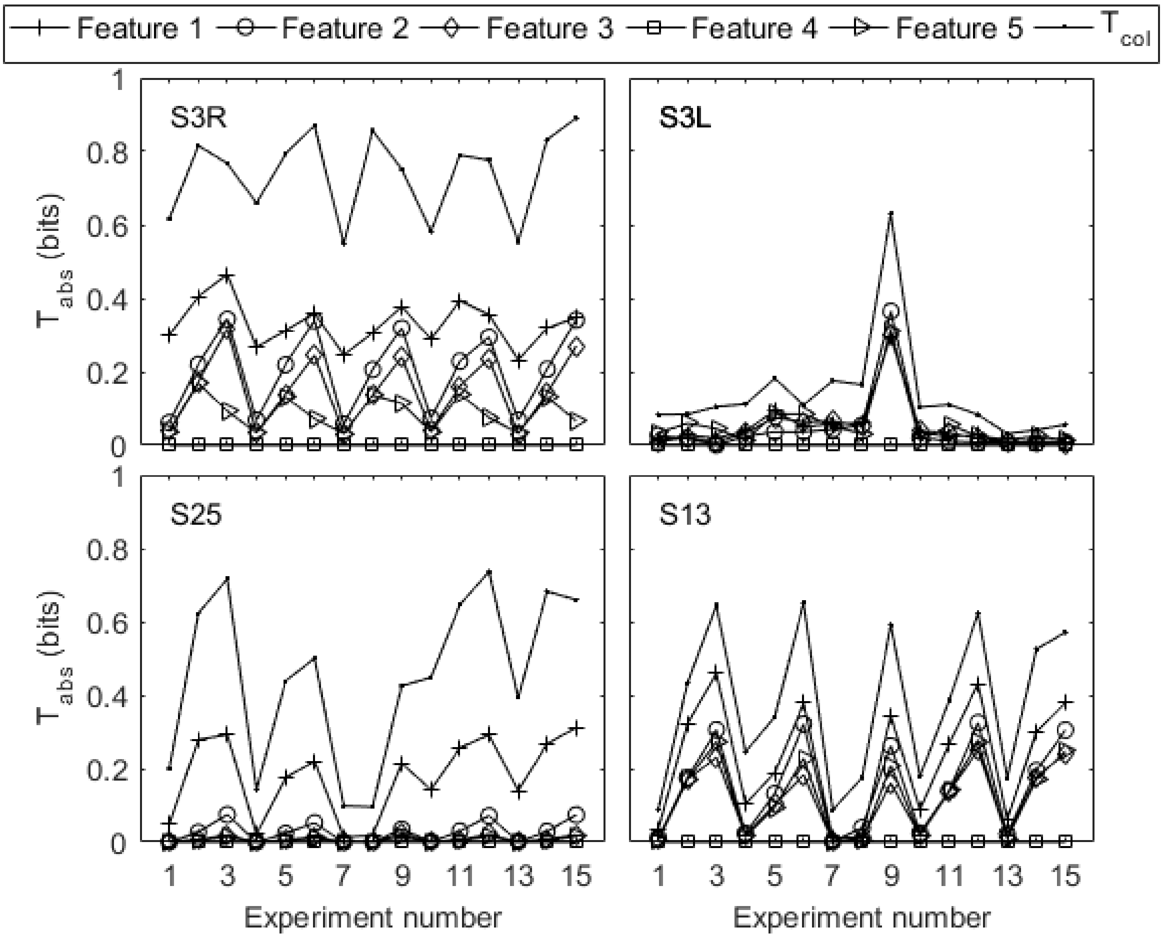


Figure 4.19 Information metrics for the different experiments of the different listeners with jndf = 480 Hz.

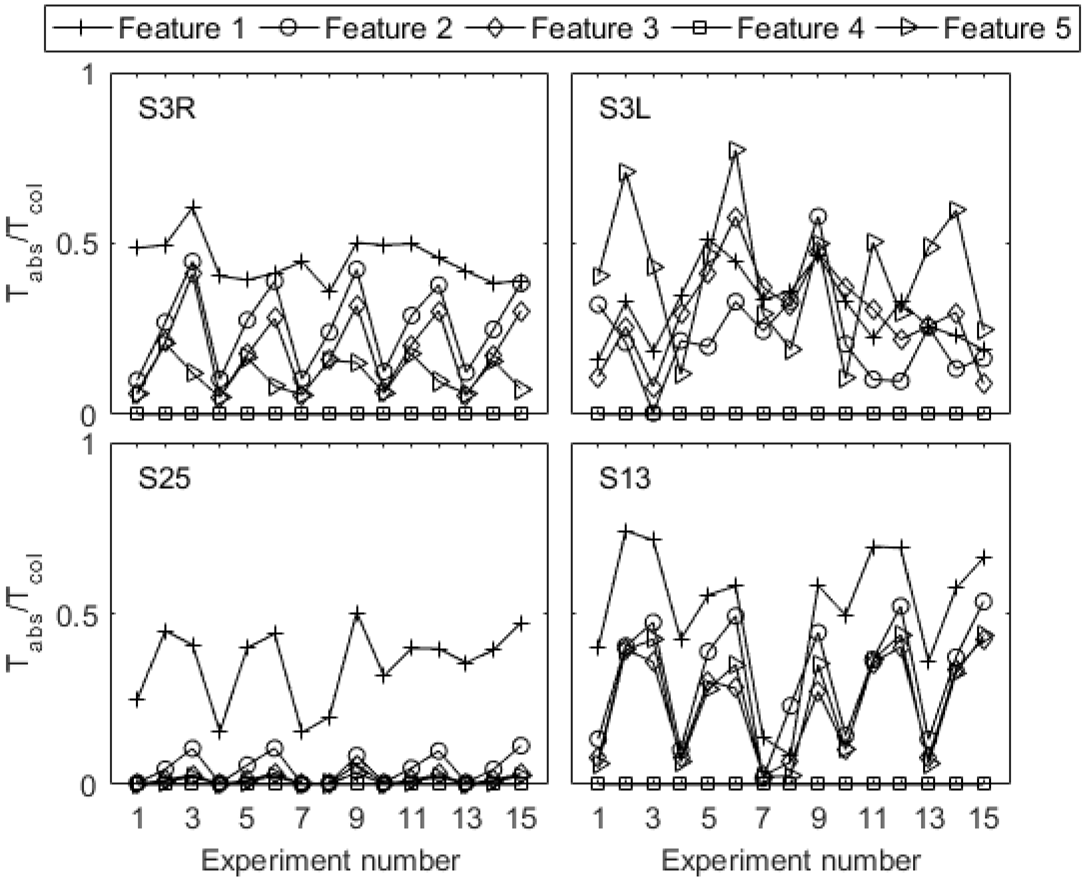


Figure 4.20 Normalised information metrics for the different experiments of the different listeners with jndf = 480 Hz.

As mentioned before, NH listeners can have jndf as small as 1 Hz. Although not realistic for CI users, the information metrics for T_{abs} was calculated with jndf = 1 Hz and the results are shown in Figure 4.21 and Figure 4.22. Compared to Figure 4.17, Figure 4.21 shows that for all the listeners and over all the experiments, T_{abs} of features 2 to 5 are closer to the magnitude of the collective transmitted information. This explains why some features in Figure 4.22 contained almost all the information used by the listeners. Figure 4.22 clearly shows that features 3 and 5 contain most information used by the listeners, while feature 4 still contains little information used by the listeners. Although these results are interesting, and keeping in mind that a jndf of 1 Hz is not a realistic choice for CI listeners, they do not complement the correlation results. The use of larger jndf values is more realistic and also corresponds more closely with data.

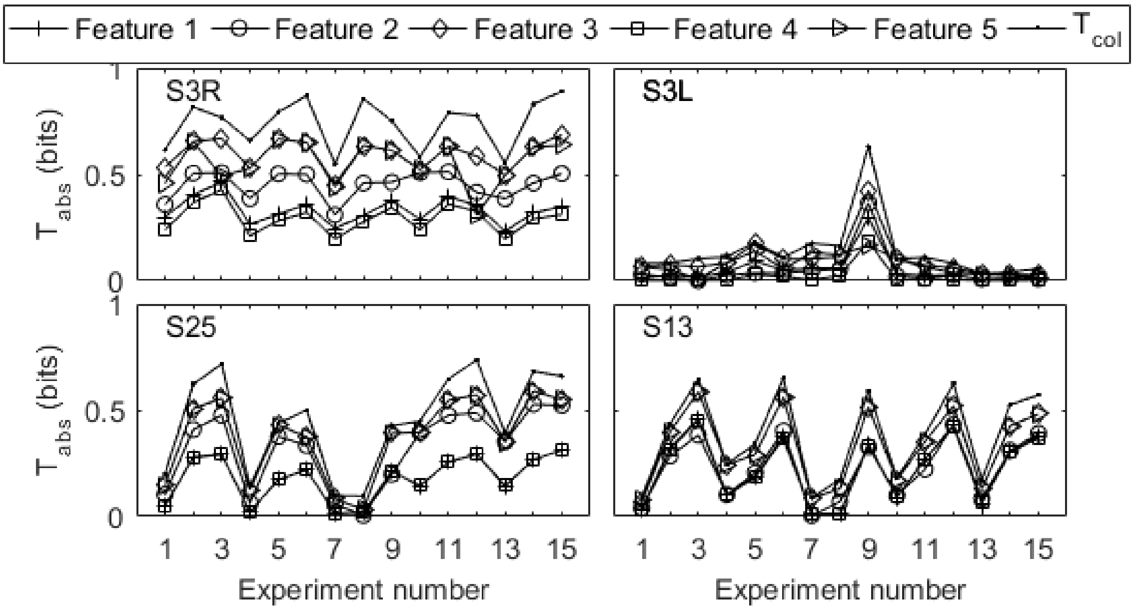


Figure 4.21 Information metrics for the different experiments of the different listeners with jndf = 1 Hz.

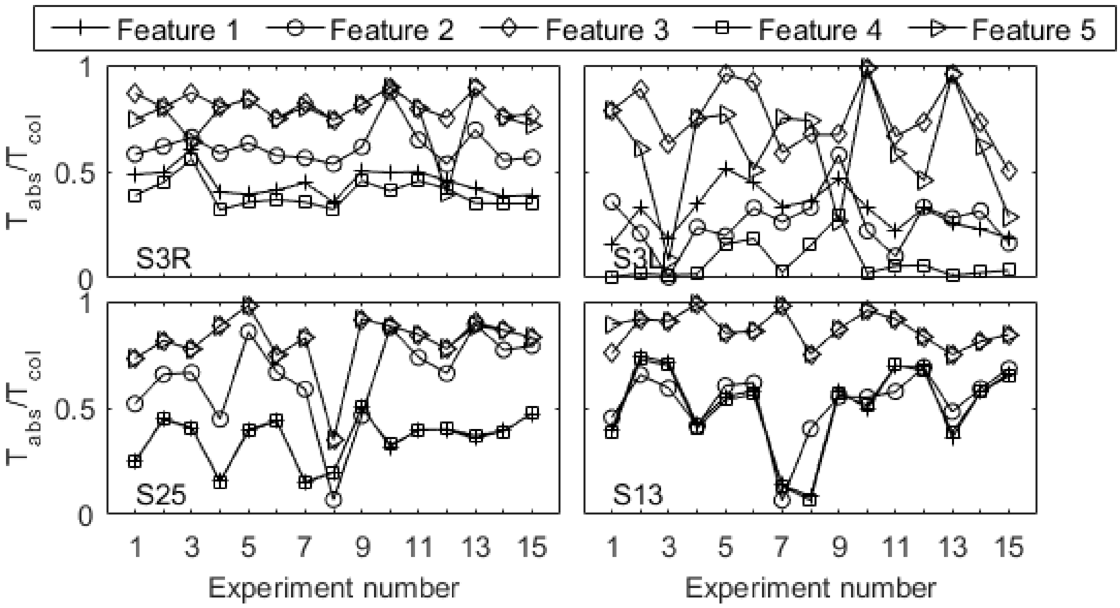


Figure 4.22 Normalised information metrics for the different experiments of the different listeners with jndf = 1 Hz.

4.4 DISCUSSION

A person-specific current distribution model was designed and used to analyse feature utilisation by relating different features proposed in literature to measured data. The objective was to determine which of the features were most likely underlying the perceived place pitch caused by the implementation of a current steering effect. Sequential stimulation was used to create a current steering effect in the present study. Literature proposed that current steering could work when sequential stimulation was used because of neural interaction (McDermott and McKay, 1994). The assumption was that the neural activation patterns of sequential stimulation, carried out within the refractory period of the neurons, could probably result in the same or very similar neural activation patterns as simultaneous stimulation. This meant that all the place pitch features proposed in current steering (using simultaneous stimulation) literature could also apply to the present study.

Two analyses were performed to analyse the feature utilisation. The consideration of the correlation results and the MI results provided complementary perspectives on the data. The correlation analysis compared the order of the results of the current steering experiments with the order of the predicted features. High correlation coefficients were obtained for most of the listeners, for most of the experiments and for all the features. Although the correlation results showed some similarity to the pitch ranking performance results (Figure 3.12) of the listeners, the correlation analysis lacks the ability to provide a true indication of the information present in the stimulus subsets used in the different experiments. The correlation analysis also fails to consider feature precision, which explains why the correlation results showed very little deviation between the results of the different features. The MI provided complementary results to address these shortfalls of the correlation analysis.

High MI was obtained for most listeners for most experiments for all the features except feature 4. The MI between feature 4 and the measured data was significantly less than the MI between the other place pitch features and the measured data. This probably suggests that the current centroid at the nerve fibre level does not carry place pitch information. When (2.1) is applied, the cochlea gives a spectral representation of sound. The place pitch is found at the place of maximum neural activation along this spectrum. Literature has shown that the brightness parameter of timbre is given by the spectral centroid (Schubert *et al.*, 2004). It has also been shown that even though there is often interaction between timbre and pitch, it is possible that there may be no interaction between the two (Krumhansl and Iverson, 1992). Because the listeners were required to listen to the place pitch, one could perhaps argue that the MI of feature 4 was low because this feature underlies timbre rather than place pitch.

The MI results highlighted the dominant effect of the electrode separation distance that was indicated by the statistical analysis in Section 3.2.4.2. The effects of the other stimulation parameters on transmitted information of listeners were also evident, as Figure 4.17 clearly shows similar data patterns to those in Figure 3.12.

The importance of choosing suitable jnd values, which determine feature precision, was evident when Figure 4.19 and Figure 4.17 were compared. A jndf of 32 Hz (Pretorius, 2011) seemed to be the most appropriate choice for the four listeners, S3R, S3L, S13 and S25, of the present study. The effect of the feature precision showed that some listeners might have preferred to use the information contained in some feature rather than that contained in other features; for example, it seemed as if listener S25 preferred to use the information contained in feature 2 rather than the other features. The correlation results also showed that there was higher correlation between feature 2 and the measured data of listener S25 than between the measured data and any of the other features.

Although feature 2 may underlie place pitch, it cannot be used directly to predict the place pitch of current-steered stimuli, because it places stimuli A and B and stimuli C and D in the same places along the auditory nerve. Even though it seemed as if listener S25 preferred to use the information contained by feature 2, this listener was still able to successfully pitch rank stimuli created using current steering under certain stimulation parameters. The fact that the mutual information of feature 2 was only slightly higher than that of features 1, 3 and 5 supports the hypothesis that these four features are different representations of the same feature. The slightly higher MI between feature 2 and the measured results of listener

S25 could suggest that although this listener relies strongly on the pitch created by the activated electrodes for place pitch perception, this listener can distinguish between the pitch of current-steered stimuli because of the integration that happens at neural level as a result of the currents applied to the stimulating electrodes.

To shortly answer the question of which of the features mentioned in literature most likely underlie place pitch, based on the above-mentioned observation: apart from feature 4, probably all of them contribute. The position of the peak current and the centroid of the current between the electrodes will lead to a specific neural activation pattern that will determine the pitch that is perceived by the listener.

4.5 SUMMARY

Literature proposes many features that might be used by listeners to perceive place pitch. This chapter discussed the current distribution model that was designed and used to relate these different features to the measured data shown in Chapter 3. The results suggested that when current steering was carried out, the place pitch was moved or changed. The listeners used the current centroid at the electrode level, the amount of current applied by each stimulating electrode, individually as well as combined, and the centre point of the neural activation area as features to determine place pitch. All four these features carried around the same amount of MI (in bits) with measured data over the different experiments for the different users, suggesting that these are the same feature expressed in different ways. The current centroid found at the auditory nerve because of current decay from the electrodes, did not have high MI with measured data. It could be that this feature did not carry place pitch information, or that the listeners did not use the place pitch information contained by this feature. The findings of Chapter 3 and Chapter 4 are brought together in Chapter 5.

CHAPTER 5 DISCUSSION AND CONCLUSION

5.1 INTRODUCTION

The major findings of the study are presented in this chapter. The research questions posed in Section 1.2 are answered in this chapter based on the findings of the present study. Possible implications of the findings of the study and possible future work are also stated briefly in this chapter.

5.2 CURRENT STEERING WITH SEQUENTIAL STIMULATION

Traditionally current steering was carried out using simultaneous stimulation (Koch *et al.*, 2007, Saoji and Litvak, 2010, Snel-Bongers *et al.*, 2011, Snel-Bongers *et al.*, 2013, Wu and Luo, 2013). Literature has shown that a current steering effect can also be achieved when sequential stimulation is used (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008). The present study confirmed the later findings and as such answered the first research question posed in Section 1.2. This is important because not all speech processors can stimulate simultaneously. It is recommended that the implementation of current steering should not be limited to speech processors that can perform simultaneous stimulation. Current steering should also be integrated in speech processing strategies of speech processors that can only stimulate with sequential stimulation, for example implants produced by Cochlear.

Current steering would typically be implemented with the aim to achieve better place pitch resolution. Improved place pitch resolution could possibly result in better speech perception and music appreciation (Green *et al.*, 2002, Gantz *et al.*, 2005, Turgeon *et al.*, 2015). Unfortunately, as observed throughout this study, current steering cannot necessarily provide additional pitch precepts for any CI user. Section 3.3 showed that current steering is not a viable solution to create additional place pitch percepts between two adjacent stimulating electrodes for CI listeners who struggle to pitch rank the pitch of two adjacent electrodes in an expected order. The results of another study also showed that listeners usually cannot accurately pitch rank an intermediate pitch if they cannot distinguish between the pitches created by two adjacent stimulating electrodes (Goehring, Neff, Baudhuin and Hughes, 2014). Based on the results of the cited study and the observation made during the present study, it is recommended that electrode pitch discrimination should be carried out before attempting to create current steering effects in a listener. It is assumed that many listeners would be excluded as participants if the requirement for implementation of current-steered stimuli during speech processing was that the listener must be able to discriminate between the pitch of adjacent electrodes. This means that unfortunately, it would typically be listeners who already do not have good place pitch resolution that would not be able to benefit from current-steered stimuli; from the results of the present study it appears one would only be able to increase the place pitch resolution of listeners who already have good place pitch resolution.

5.3 MDS OR SENSITIVITY INDEX?

Many studies use cumulative d' to evaluate the perceptual distance between stimuli presented to CI listeners during pitch ranking experiments. The present study considered both MDS and cumulative d' values to evaluate the perceptual distance between the stimuli presented during the pitch ranking experiments described in Section 3.2.

In Section 3.2.2 the stress factor of the MDS showed that the perceptual data of the pitches of the different stimuli could be presented in a single dimension. This means that d' values should sufficiently describe the perceptual distance between the pitches of the different stimuli. However, Section 3.2.3 showed that this was not always the case. Based on the observation made in this study, it is recommended that cumulative d' values rather than MDS should be used, with caution. The use of cumulative d' values is more time-efficient and they should be used when the perceptual order (from low to high or vice versa) of pitches is known (i.e., not assumed) and when it is known that the perceptual distance between the pitch of the stimuli would most likely be large. When precision of perceptual distance and the deduction of an unbiased ranking order are more important than the time taken by the experiments, it is recommended rather to consider the use of MDS as the method of analysis.

5.4 EFFECT OF DIFFERENT STIMULATION PARAMETERS

The second research question was if stimulation parameters determine pitch ranking ability when sequential stimulation is used to steer current and are there more effective and less effective choices for stimulation parameters? The present study showed that in all the results of the different listeners, the most influential factors were the person-specific ones, this could typically include the structure of the cochlea, neural survival patterns and the way the electrode is inserted into the cochlea (Chatterjee and Shannon, 1998, Loizou, 1999, Laneau and Wouters, 2004, Macherey and Carlyon, 2012). The results also showed that certain stimulation parameters did improve the pitch ranking ability of the CI users who participated in the pitch ranking tasks presented in Section 3.2. The effect of different stimulation parameters on the results was different for each listener. This section highlights some important thoughts and conclusions on the effects of different stimulation parameters.

Electrode separation distance. Most listeners benefited from current steering when larger electrode separation distances were used between stimulating electrodes. This observation has two possible implications. Firstly, current steering could possibly successfully be used to improve the pitch resolution of CI users implanted with electrodes that are spread further away from each other than those implanted in the listeners who participated in the present study. An example of an electrode array that have larger separation distances between the electrodes is the Standard Med-El electrode array from their Classic series (Cochlear, 2012).

Secondly, in cases where a single electrode fails, the pitch resolution that would normally have resulted from this electrode could be restored. Current can be steered to the locations that would normally be targeted by the malfunctioning electrode by stimulating the two electrodes on either side of the malfunctioning electrode. Another study has shown that for a signal with equal proportions of current delivered to two non-adjacent electrodes, pitch is equivalent to that produced by an intermediate physical electrode (Snel-Bongers *et al.*, 2011). Although the cited study was carried out using simultaneous stimulation, the findings of the present study gives reason to believed that it would be possible to create the same effect using sequential stimulation.

Stimulation pulse rate. The results of most users improved significantly in experiments where the stimulation pulse rate was the same as the stimulation rate indicated in the clinical MAP of the CI user (see Section 3.2.4.2 and Section 3.2.4.3). Given the available data it seems as if it could be beneficial to stimulate at the rate indicated on the clinical MAP of the CI listener to achieve optimal pitch ranking results when stimuli are created with the aim of achieving a current steering effect. However, the amount of available data is not enough to attach significance to this deduction. Interestingly, another study that measured the effect of stimulation rate on phoneme and speech recognition of CI users found that the listeners who participated in their study also performed best when the original rate of the processor of the listeners was used (Friesen, Shannon and Cruz, 2005).

Stimulation mode. The effect of the stimulation mode, inter-pulse delay and the delay between pulses on the two stimulating electrodes was not tested by the experiments done in the present study. Increasing knowledge about the effect of a wide variety of stimulation parameters can lead to more effective implementation of current steering with sequential stimulation.

Although most modern-day implants make use of monopolar stimulation, the effect of bipolar stimulation on the perception of pitch, created by current-steered stimuli, in comparison with monopolar stimulation, is unclear. Current distribution through the cochlea differs greatly when monopolar mode versus bipolar mode is used for stimulation (Zhu, Tang, Zeng, Guan and Ye, 2012). Current distribution through the cochlea critically affects the perception of sounds, therefore it could be valuable to test the effect of stimulation mode on the performance of CI listeners during current steering experiments.

Future work should investigate the effect of stimulation mode, through modelling and through experiments. The existing person-specific volume conduction model (Malherbe *et al.*, 2015) would be a good start for such an investigation. The effect on current distribution throughout the cochlea can be investigated using the model.

Inter-stimuli time delay. Literature hypothesise that the time between pulses on the two stimulating electrodes should be shorter than the refectory period of the neurons to achieve a current steering effect when sequential stimulation is used (McDermott and McKay, 1994). Keeping this time short opens the possibility for neural interaction, which is crucial to achieve a current steering effect with sequential stimulation. The effect of longer and shorter delays between pulses on the two stimulating electrodes was, however, not tested experimentally. Experiments should be carried out in a future study to confirm the hypothesis proposed in literature. Such experiments can also include an investigation of the effect of the pulse phase conditions. The experiments should typically include an investigation into the effect of using spread mode with a slow stimulation rate on the effectivity of current steering. A current steering effect should not be achievable with these stimulation parameters if the experiments confirmed that a current steering effect can only be achieved when the stimulation delay between the two stimulating electrodes is smaller than the refractory period of the neurons.

5.5 FEATURES UNDERLYING PLACE PITCH

This section discusses the last two research questions posed in Section 1.2. Place pitch can be steered by steering current between two stimulating electrodes (Firszt *et al.*, 2007). Literature suggested a number of stimulus features that may underlie place pitch during electrical stimulation (McDermott and McKay, 1994, Kwon and van den Honert, 2006, Swanson, 2008, Frijns *et al.*, 2009, Macherey and Carlyon, 2012, Venter, 2015). Five features were investigated and compared with data in Chapter 4. All five the features correlated highly with measured results. MI results showed that high transmitted information values were reported for the position of the current centroid at electrode level, the peak current position along the auditory nerve, because of each stimulating electrode as well as the summed current of the two electrodes and the position of the centroid of neural activation. Low transmitted information values were reported for the current centroid at nerve fibre level, suggesting that this feature was not used by the listeners during the place pitch ranking task of the current steering experiments.

The auditory nerve can carry a spectral representation of sounds (Cosentino, McAlpine, Marquardt and Falk, 2014). This means that feature 4 could perhaps be related to a spatially-represented spectral centroid. Literature often discusses how the spectral centroid is a feature that encodes the brightness parameter of timbre (Schubert *et al.*, 2004). It is possible that feature 4 rather underlies timbre, while the other four features relate more closely to place pitch features. This observation confirms that current steering shifts place pitch.

In hindsight it seems obvious that the four features with high information transmission values are the same feature expressed in different ways, because pitch perception is entirely dependent on the action potential patterns at the neural level. Because of the stimulation current applied to each stimulating electrode, there will be a current centroid between the two stimulating electrodes. The stimulation on the electrodes and the centroid will lead to a certain current distribution and the current reaching the auditory nerve will result in a neural activation pattern which would determine the perceived place pitch.

To obtain better understanding about the auditory system and how place pitch is perceived in the auditory system, one would have to consider neural activation patterns, which necessitates the availability of accurate volume condition and neural models. However, a fortunate implication of the small variation between the MI of the different features and measured place pitch investigated is that any one of these four features could be used to predict place pitch. Even without the availability of a neural model, for example, the centroid of current between two stimulating electrodes would correlate with place pitch. This explains why previous literature (Laneau *et al.*, 2004) found good correspondence between place pitch and predicted current centroid. However, as explained in Section 4.4 feature 2 cannot necessarily be used to predict the place pitch of current-steered stimuli, because even though it simulates place pitch, it does not simulate any current steering effect.

In summary, the main findings of the present study are listed below.

- It was confirmed that a current steering effect could be created when sequential stimulation is used.
- Some stimulation parameters may lead to more effective current steering with sequential stimulation, for example using the same stimulation rate as indicated on the clinical MAP of the listener or using wider electrode separation distances may improve the pitch ranking ability of current-steered stimuli by CI listeners.
- A single dimension can sufficiently represent the perceptual distance of pitch between two stimulating electrodes. This means that cumulative d' values can be used to analyse pitch ranking results of current-steered stimuli. However, this should be done with caution. If highly accurate perceptual distances and unbiased pitch ranks are crucial, MDS analysis should be considered as the preferred method.
- Current steering controls and steers place pitch.
- All the features proposed by literature, except the current centroid at the auditory nerve level, underlie place pitch. Features 1, 2, 3 and 5 are the same feature expressed in different ways.

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APPENDIX A

A.1 INTRODUCTION

Prior to executing the psychoacoustic experiments discussed in Chapter 3, pilot experiments were carried out to gain understanding of the influence of different stimulation parameters on the pitch ranking ability of CI listeners of stimuli created with the aim to achieve current steering effects. The pilot experiments were used to eliminate stimulation parameters that would have little effect on the pitch ranking ability of CI listeners. By doing this, the number of experiments that had to be carried out and the execution time of the psychoacoustic experiments were limited. Only listener S15 participated in the pilot experiments. This appendix provides more detail on the setup and results of the pilot experiments.

A.2 METHOD

Table A.1 gives a summary of the parameters that were used for stimulation during the pilot experiments.

Table A.1 Stimulation parameters tested during each pilot experiment.

Pilot experiment number	Mode	Stimulation level	Pulse width	Pulse rate	Electrode separation distance
1	Burst	75% dynamic range	25 µs	1776 pps	1
2	Burst	75% dynamic range	25 µs	1776 pps	2
3	Burst	75% dynamic range	25 µs	1776 pps	3
4	Spread	75% dynamic range	25 µs	1776 pps	1
5	Spread	75% dynamic range	25 µs	1776 pps	2
6	Spread	75% dynamic range	25 µs	1776 pps	3
7	Burst + Spread	75% dynamic range	133 µs	1776 pps	1
8	Burst + Spread	75% dynamic range	133 µs	1776 pps	2
9	Burst + Spread	75% dynamic range	133 µs	1776 pps	3
10	Burst	75% dynamic range	25 µs	200 pps	1
11	Burst	75% dynamic range	25 µs	200 pps	2
12	Burst	75% dynamic range	25 µs	200 pps	3
13	Spread	75% dynamic range	25 µs	200 pps	1
14	Spread	75% dynamic range	25 µs	200 pps	2

Table A.1 continues

Pilot experiment number	Mode	Stimulation level	Pulse width	Pulse rate	Electrode separation distance
15	Spread	75% dynamic range	25 µs	200 pps	3
16	Burst	100% dynamic range	25 µs	1776 pps	1
17	Burst	100% dynamic range	25 µs	1776 pps	2
18	Burst	100% dynamic range	25 µs	1776 pps	3
19	Spread	100% dynamic range	25 µs	1776 pps	1
20	Spread	100% dynamic range	25 µs	1776 pps	2
21	Spread	100% dynamic range	25 µs	1776 pps	3

The experimental setup for the pilot experiments was the same as that of the psychoacoustic experiments discussed in Chapter 3. During the pilot experiments the CI listener also had to complete a dynamic range estimation task, a loudness balancing task and a pitch ranking task.

A.3 RESULTS

The pitch ranking results of the pilot experiments are shown in Figure A.1. The percentage correct values in the graph were calculated as described in Section 3.2.4 and used to compare the results of the different pilot experiments. Because the objective of the pilot experiments was simply to gain better understanding of the influence of different stimulation parameters, no in-depth analysis of the results was carried out.

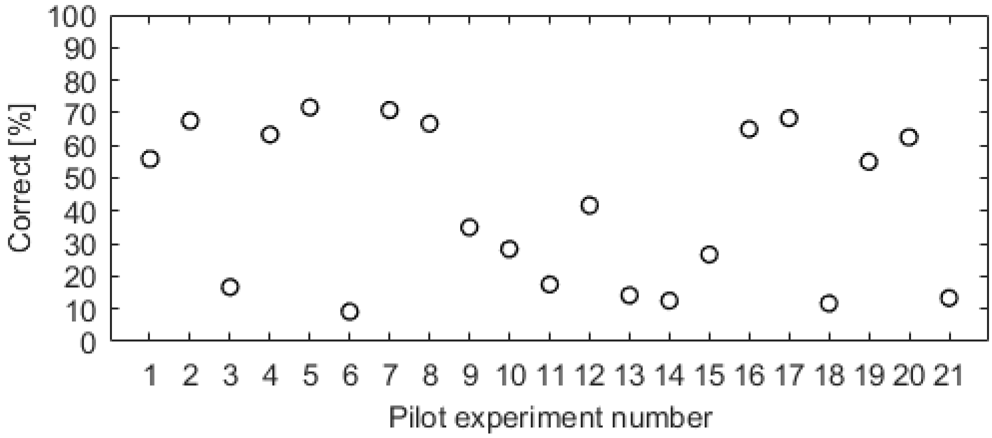

Figure A.1. Percentage correct responses (according to the hypothesis discussed in Chapter 3) during the pitch ranking section of the pilot experiments.

A.4 DISCUSSION AND CONCLUSION

In Figure A.1 and Figure A.2, 100% means that the listener responded as expected, 50% is the chance performance level and 0% means that the listener always indicated that the opposite stimulus from the expected one was higher in pitch.

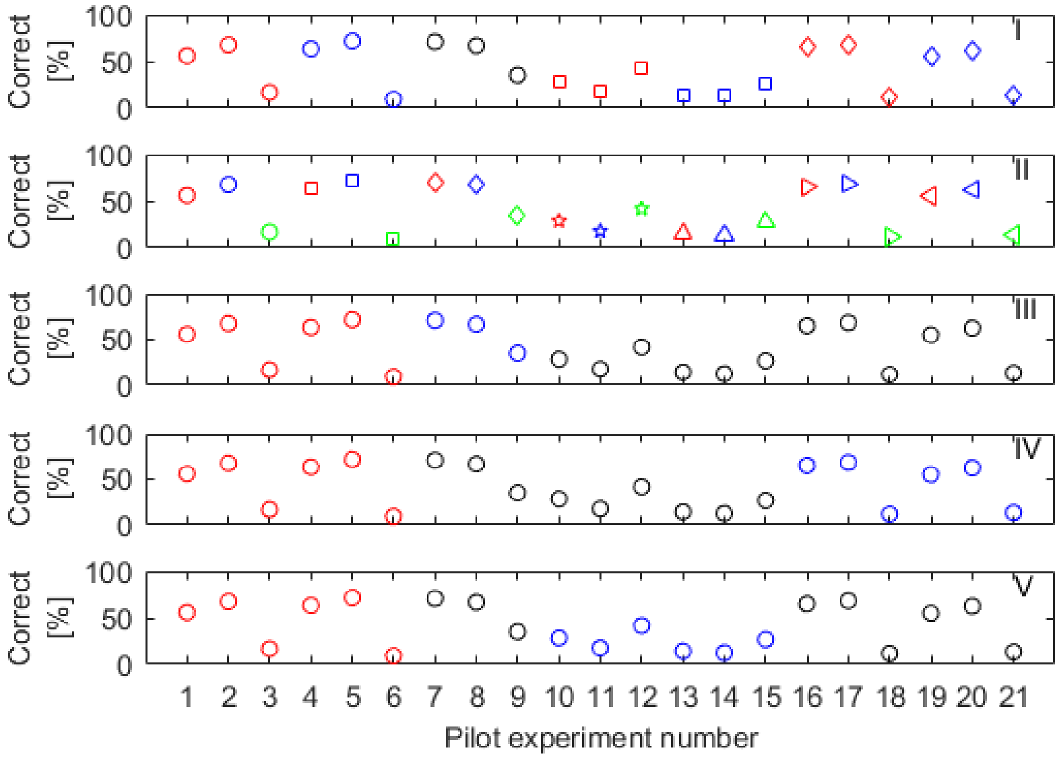

Figure A.2. Percentage correct responses (according to the hypothesis discussed in Chapter 3) during the pitch ranking section of the pilot experiments. Each panel in this figure shows the same results as those in Figure A.1. This figure was added as a visual aid for the comparison and discussion of various stimulation parameters. Each panel is used to discuss a different stimulation parameter: I burst and spread mode, II electrode separation distance, III stimulation pulse width, IV stimulation amplitude level and V stimulation pulse rate. Red symbols were used as the reference experiments. The experiments marked in blue or green were compared to the reference experiments. Black circles show the experiments that were not included in the discussion of that specific stimulation parameter. Different shapes were not compared to each other; for example in panel I, the blue circles were compared to the red circles and the blue squares to the red squares, but the red circles and the red squares or the blue circles and the blue squares were not compared to each other.

During the pilot experiments the absolute percentage correct value was not as important as the relative difference between experiments. If the relative difference between experiments was large when all but one stimulation parameter was changed, it was assumed that the stimulation parameter could have an effect on the pitch ranking ability of CI listeners during current steering experiments; if the relative difference between experiments was small when all but one stimulation parameter was changed, it was assumed that that stimulation parameter probably would not have an effect on the pitch ranking ability of CI listeners during current steering experiments.

Consider panel I of Figure A.2. Comparison of experiments 1, 2 and 3 (red circles) with experiments 4, 5 and 6 (blue circles) respectively, experiments 10, 11 and 12 (red squares) with experiments 13, 14 and 15 (blue squares) respectively, and experiments 16, 17 and 18 (red diamonds) with 19, 20 and 21 (blue diamonds) respectively, shows that there is almost no difference in the experimental results when burst mode is used compared to when spread mode is used.

Panel II of Figure A.2 highlights the effect of the electrode separation distance. An electrode separation distance of one electrode was marked by red circles, two electrodes were marked by blue circles and the green circles indicate an electrode separation distance of three electrodes. Panel II of Figure A.2 shows that the electrode separation distance has a noticeable effect on the percentage correct results. This conclusion was reached because there are large differences between the percentage correct values when for example experiments 1, 2, and 3 are compared (circles) or experiments 4, 5 and 6 are compared (squares).

Considering Panel III of Figure A.2, if the first six experiments (red circles) are used as reference experiments, changing the pulse width of the stimuli from 25 µs to 133 µs (experiments 7, 8 and 9 indicated with blue circles) had an effect on pitch ranking ability. When a pulse rate of 133 µs was used compared to when a pulse rate of 25 µs was used, the percentage correct results improved where an electrode separation distance of three

electrodes was used. When a pulse rate of 25 µs was used the listeners' pitch ranking performance was better when an electrode separation distance of two electrodes was used, compared to when a separation distance of one electrode was used. However, when the pulse rate was increased to 133 µs, the pitch ranking performance of the listener was at its best when an electrode separation distance of one electrode was used.
Changing the amplitude from 75% of the dynamic range (experiments 1 to 6 marked with red circles in panel IV of Figure A.2) to 100% of the dynamic range (experiments 16 to 21 marked with blue circles in panel IV of Figure A.2) seemed to have almost no effect on the results.

Consider panel V of Figure A.2. Changing the stimulation pulse rate from 1776 pps (experiments 1 to 6 marked with red circles) to 200 pps (experiments 10 to 15 marked with blue circles) seemed to have a large effect on the results. The pitch ranking performance was considerably better at an electrode separation distance of one or two electrodes when a pulse rate of 1776 pps was used compared to when a pulse rate of 200 pps was used. The pitch ranking performance was slightly better at an electrode separation distance of three electrodes when a pulse rate of 200 pps was used compared to when a stimulation rate of 1776 pps was used. On average, the pitch ranking performance of the listener was better at the higher stimulation rate than at the lower stimulation rate.

Results of the pilot experiments suggested that stimulation pulse rate, electrode separation distance and stimulation pulse width are the primary parameters that would influence pitch ranking ability when attempting to achieve a current steering effect with sequential stimulation. The stimulation amplitude and whether burst or spread mode was used did not seem to influence the pitch ranking ability of the listener markedly. For these reasons, stimulation pulse rate, electrode separation distance and stimulation pulse width were the stimulation parameters selected for inclusion in the final experiments.

APPENDIX B

B.1 INTRODUCTION

CU is the measurement unit used by Cochlear for the amount of current applied to the stimulating electrode of the cochlear implant. CUs can be related to current using a function that depends on the specific CI integrated circuitry (IC, or "chip"). The CI24M and CI24R model CIs are based on the CIC3 CI chip and the CI24RE CI is based on the CIC4 CI chip (Botros, Van and Killian, 2008). All three these CIs are products of Cochlear Ltd. The CU-to-current conversion functions for the CIC3 CI chip and the CIC4 CI chip are described in this appendix.

B.2 CU-TO-CURRENT CONVERSION FUNCTION

The CU-to-current conversion function for the CIC3 CI chip is given by

$$I(\mu A) = I_{min} \times e^{CU \times \frac{\ln\left(\frac{I_{max}}{I_{min}}\right)}{CU_{max}}}, \quad \text{(B.1)}$$

where I_{min} is the minimum output current (10 µA at 0 CU), CU is the CUs, I_{max} is the maximum output current (1750 µA at 255 CU) and CU_{max} is the maximum CU value $2^8 - 1 = 255$[4]. The function is simplified to

$$I(\mu A) = 10 \times e^{CU \times \frac{\ln(175)}{225}}. \quad \text{(B.2)}$$

The CU-to-current conversion function for the CIC4 CI chip is described by

$$I(\mu A) = I_{min} \times 100^{\frac{CU}{CU_{max}}}, \quad \text{(B.3)}$$

[4] This equation was obtained from the MATLAB nucleus toolbox (Swanson, 2008).

where CU_{max} is still equal to 255 but I_{min} is now equal to 17.5 μA. Equation (B.3) is simplified to

$$I(\mu A) = 17.5 \times 100^{\frac{CU}{255}}. \tag{B.4}$$

APPENDIX C

C.1 INTRODUCTION

This appendix presents tables containing details of the results of the statistical analysis presented and discussed in Section 3.2.4.2. The results are not interpreted or discussed in this appendix, since this has already been done in Section 3.2.4.2.

C.2 STATISTICAL RESULTS

C.2.1 Multi-listener analysis (overall analysis)

Table C.2, Table C.3 and Table C.4 show the type III test of fixed effects, the estimate of fixed effects and the estimate of covariance parameters of the multi-listener analysis respectively.

Table C.2. Type III test of fixed effects of the multi-listener analysis.

Source	Numerator df	Denominator df	F	Sig
Intercept (Listener)	1	9.749	190.109	0.000
Pulse rate (PR)	2	67.820	0.372	0.691
Pulse width (PW)	2	24.857	0.952	0.399
Electrode separation distance (ED)	2	89.971	6.760	0.002

Table C.3. Estimate of fixed effects of the multi-listener analysis.

Parameter	Estimate	Std. Error	Df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept (Listener)	72.381176	5.021509	10.877	14.414	0.000	61.313694	83.448657
[PR=200.00]	-0.909592	3.411570	49.467	-0.267	0.791	-7.763762	5.944579
[PR=888.00]	-2.521160	3.045428	79.358	-0.828	0.410	-8.582507	3.540188
[PR=1776.00]	0	0	.	.	.	.	.
[PW=25.00]	-5.548073	4.161961	10.828	-1.333	0.210	-14.72632	3.630175
[PW=79.00]	-1.068731	3.045428	79.358	-0.351	0.727	-7.130078	4.992616
[PW=132.00]	0	0	.	.	.	.	.
[ED=1.00]	-6.992103	1.903307	91.289	-3.674	0.000	-10.77263	-3.211578
[ED=2.00]	-3.255593	1.820296	88.817	-1.788	0.077	-6.872585	0.361399
[ED=3.00]	0	0	.	.	.	.	.

Table C.4. Estimate of covariance parameters of the multi-listener analysis.

Parameter	Estimate	Std. Error	Walt Z	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Repeated Measures	112.465605	17.830681	6.307	0.00	82.426588	153.451849
Intercept + Experiment (Subject = Listener)	316.946148	175.123278	1.810	0.07	107.316955	936.057687

C.2.2 Individual analysis

A summary of the statistical results of the multi-level model analysis of the individual listeners was given in Table 3.8. More comprehensive results of the multi-level model analysis of the individual listeners are presented in Table C.5 to Table C.15. Table C.5 shows the type III test of fixed effects for each subject for each stimulation parameter. Table C.6 to Table C.15 shows the estimates of fixed effects for the individual listeners.

Table C.5 Type III test of fixed effects for each subject for each stimulation parameter.

Subject	Pulse rate	Pulse width	Electrode separation distance
S1R	F(2,9.745)=40.647, p<0.0005	F(2,9.900)=27.007, p<0.0005	F(2,14.846)=1.276, p=0.308
S1L	F(2,8.218)=35.983, p<0.0005	F(2,8.298)=4.987, p=0.038	F(2,14.477)=2.822, p=0.092
S2	F(2,8.844)=19.483, p=0.001	F(2,8.864)=1.373, p=0.302	F(2,13.895)=10.056, p=0.002
S3	F(2,10.232)=68.181, p<0.0005	F(2,10.413)=0.603, p=0.565	F(2,13.249)=63.506, p<0.0005
S4	F(2,9.956)=19.888, p<0.0005	F(2,10.137)=202.778, p<0.0005	F(2,13.793)=1.490, p=0.260
S5	F(2,9.054)=1.997, p=0.191	F(2,9.209)=1.702, p=0.235	F(2,14.916)=0.133, p=0.876
S6	F(2,8.199)=2.273, p=0.164	F(2,7.165)=20.687, p=0.001	F(2,8.788)=13.717, p=0.002
S7	F(2,7.726)=24.399, p<0.0005	F(2,6.969)=3.832, p=0.075	F(2,8.918)=58.555, p<0.0005
S8	F(2,2.082)=36.781, p=0.024	F(2,2.221)=25.039, p=0.030	F(2,13.724)=69.632, p<0.0005
S9	F(2,10.131)=255.922, p<0.0005	F(2,10.272)=130.952, p<0.0005	F(2,14.933)=3.200, p=0.070

Table C.6. Estimates of fixed effects for listener S3R.

Parameter	Estimate	Std. Error	df	T	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	87.40296	.621329	13.475	140.671	.000	86.065446	88.740465
[PR=200.00]	-5.20559	.604804	9.651	-8.607	.000	-6.559822	-3.851364
[PR=888.00]	-4.17265	.635564	10.034	-6.565	.000	-5.588113	-2.757180
[PR=1776.00]	0	0	.	.	.	.	.
[PW=25.00]	4.491848	.613845	9.944	7.318	.000	3.123072	5.860624
[PW=79.00]	2.820113	.635564	10.034	4.437	.001	1.404646	4.235579
[PW=132.00]	0	0	.	.	.	.	.
[ED=1.00]	-1.09087	.742808	14.626	-1.469	.163	-2.677656	.495920
[ED=2.00]	-.107929	.788480	14.935	-.137	.893	-1.789169	1.573311
[ED=3.00]	0	0	.	.	.	.	.

Table C.7. Estimates of fixed effects for listener S3L.

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	56.78455	3.04549	13.31	18.65	.000	50.220446	63.348647
[PR=200.00]	16.555974	3.140178	7.919	5.272	.001	9.301865	23.810082
[PR=888.00]	-10.57644	3.277110	8.612	-3.23	.011	-18.04094	-3.111936
[PR=1776.00]	0	0	.	.	.	.	.
[PW=25.00]	2.464923	3.172897	8.297	.777	.459	-4.806443	9.736288
[PW=79.00]	-7.220605	3.277110	8.612	-2.20	.056	-14.68511	.243895
[PW=132.00]	0	0	.	.	.	.	.
[ED=1.00]	-6.313375	3.520717	14.901	-1.79	.093	-13.82195	1.195195
[ED=2.00]	-8.197873	3.682786	14.172	-2.23	.043	-16.08769	-.308058
[ED=3.00]	0	0	.	.	.	.	.

Table C.8. Estimates of fixed effects for listener S25.

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	88.72613	2.72202	13.53	32.60	.000	82.868742	94.583519
[PR=200.00]	-17.96234	2.881221	8.444	-6.23	.000	-24.54612	-11.37856
[PR=888.00]	-8.277808	2.994521	9.267	-2.76	.021	-15.02228	-1.533334
[PR=1776.00]	0	0	.	.	.	.	.
[PW=25.00]	-3.635843	2.905107	8.827	-1.25	.243	-10.22735	2.955662
[PW=79.00]	.825561	2.994521	9.267	.276	.789	-5.918913	7.570035
[PW=132.00]	0	0	.	.	.	.	.
[ED=1.00]	-13.72062	3.078996	14.543	-4.46	.000	-20.30137	-7.139876
[ED=2.00]	-5.448073	3.197374	13.503	-1.70	.111	-12.32950	1.433349
[ED=3.00]	0	0	.	.	.	.	.

Table C.9. Estimates of fixed effects for listener S13.

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	93.55577	1.63690	12.72	57.15	.000	90.011395	97.100140
[PR=200.00]	-15.8466	1.51363	10.262	-10.5	.000	-19.20751	-12.48566
[PR=888.00]	-1.126619	1.597696	10.441	-.705	.496	-4.666230	2.412991
[PR=1776.00]	0	0	.	.	.	.	.
[PW=25.00]	-1.417958	1.542705	10.486	-.919	.379	-4.833835	1.997919
[PW=79.00]	-1.593447	1.597696	10.441	-.997	.341	-5.133058	1.946163
[PW=132.00]	0	0	.	.	.	.	.
[ED=1.00]	-22.3049	1.987472	13.080	-11.2	.000	-26.59592	-18.01389
[ED=2.00]	-13.0935	2.129938	13.344	-6.15	.000	-17.68293	-8.504059
[ED=3.00]	0	0	.	.	.	.	.

Table C.10. Estimates of fixed effects for listener S24.

Parameter	Estimate	Std. Error	df	T	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	75.01211	1.022019	12.911	73.396	.000	72.802627	77.221584
[PR=200.00]	-3.80993	.958001	9.958	-3.977	.003	-5.945715	-1.674139
[PR=888.00]	2.310897	1.010155	10.192	2.288	.045	.065876	4.555918
[PR=1776.00]	0	0	.	.	.	.	.
[PW=25.00]	-17.0546	.975243	10.204	-17.49	.000	-19.22171	-14.88750
[PW=79.00]	-.787103	1.010155	10.192	-.779	.454	-3.032124	1.457917
[PW=132.00]	0	0	.	.	.	.	.
[ED=1.00]	-1.55303	1.237524	13.543	-1.255	.231	-4.215668	1.109619
[ED=2.00]	.610314	1.323644	13.929	.461	.652	-2.229976	3.450603
[ED=3.00]	0	0	.	.	.	.	.

Table C.11. Estimates of fixed effects for listener S19.

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	45.07394	2.535857	13.282	17.775	.000	39.607372	50.540515
[PR=200.00]	4.315606	2.486848	8.933	1.735	.117	-1.316429	9.947641
[PR=888.00]	4.479240	2.611330	9.369	1.715	.119	-1.392703	10.351182
[PR=1776.00]	0	0	.	.	.	.	.
[PW=25.00]	-2.98526	2.522578	9.251	-1.183	.266	-8.668233	2.697711
[PW=79.00]	1.514679	2.611330	9.369	.580	.576	-4.357263	7.386621
[PW=132.00]	0	0	.	.	.	.	.
[ED=1.00]	-.882341	3.021491	14.706	-.292	.774	-7.333711	5.569028
[ED=2.00]	.758836	3.201678	14.986	.237	.816	-6.065933	7.583605
[ED=3.00]	0	0	.	.	.	.	.

Table C.12. Estimates of fixed effects for listener S28.

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	58.349908	4.809870	9.260	12.131	.000	47.515672	69.184144
[PR=200.00]	2.652405	5.861706	6.590	.452	.665	-11.38521	16.690017
[PR=888.00]	-9.034581	5.773825	9.222	-1.565	.151	-22.04806	3.978900
[PR=1776.00]	0	0	.	.	.	.	.
[PW=25.00]	-34.48710	5.867910	6.292	-5.877	.001	-48.68515	-20.28904
[PW=79.00]	-3.581556	5.773825	9.222	-.620	.550	-16.59504	9.431926
[PW=132.00]	0	0	.	.	.	.	.
[ED=1.00]	19.245158	4.151723	9.790	4.635	.001	9.967566	28.522749
[ED=2.00]	.949413	4.118399	8.359	.231	.823	-8.477017	10.375842
[ED=3.00]	0	0	.	.	.	.	.

Table C.13. Estimates of fixed effects for listener S6.

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	57.039368	2.249887	9.926	25.352	.000	52.021269	62.057467
[PR=200.00]	-14.39055	2.698774	6.381	-5.332	.001	-20.89984	-7.881256
[PR=888.00]	3.319438	2.692532	8.600	1.233	.250	-2.814986	9.453861
[PR=1776.00]	0	0	.	.	.	.	.
[PW=25.00]	7.318617	2.698843	6.339	2.712	.033	.799537	13.837698
[PW=79.00]	4.943606	2.692532	8.600	1.836	.101	-1.190818	11.078029
[PW=132.00]	0	0	.	.	.	.	.
[ED=1.00]	-19.19968	2.060088	9.996	-9.320	.000	-23.79010	-14.60926
[ED=2.00]	.195104	2.057284	8.451	.095	.927	-4.505258	4.895467
[ED=3.00]	0	0	.	.	.	.	.

Table C.14. Estimates of fixed effects for listener S20.

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	81.735366	1.312330	6.314	62.283	.000	78.56253	84.90820
[PR=200.00]	-8.051105	1.281788	1.884	-6.281	.028	-13.90367	-2.19854
[PR=888.00]	-11.00224	1.346513	2.086	-8.171	.013	-16.57174	-5.43274
[PR=1776.00]	0	0	.	.	.	.	.
[PW=25.00]	8.869797	1.300608	2.033	6.820	.020	3.360178	14.37942
[PW=79.00]	2.674392	1.346513	2.086	1.986	.180	-2.895107	8.243892
[PW=132.00]	0	0	.	.	.	.	.
[ED=1.00]	-18.11467	1.566553	11.868	-11.56	.000	-21.53210	-14.69724
[ED=2.00]	-5.604441	1.661558	14.577	-3.373	.004	-9.154946	-2.05394
[ED=3.00]	0	0	.	.	.	.	.

Table C.15. Estimates of fixed effects for listener S5.

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	81.60539	1.344713	13.696	60.686	.000	78.715262	84.495524
[PR=200.00]	28.36855	1.317867	10.021	21.526	.000	25.432990	31.304113
[PR=888.00]	6.214662	1.383929	10.416	4.491	.001	3.147694	9.281629
[PR=1776.00]	0	0	.	.	.	.	.
[PW=25.00]	-21.4750	1.336869	10.311	-16.06	.000	-24.44165	-18.50842
[PW=79.00]	-9.39333	1.383929	10.416	-6.787	.000	-12.46029	-6.326357
[PW=132.00]	0	0	.	.	.	.	.
[ED=1.00]	-4.02974	1.602723	14.775	-2.514	.024	-7.450401	-.609073
[ED=2.00]	-1.59512	1.698564	14.987	-.939	.363	-5.215796	2.025550
[ED=3.00]	0	0	.	.	.	.	.